The effect of increased land use intensification on the physical properties of a silt loam topsoil.

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Abstract

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Since settlers first arrived land use has been continually changing across New Zealand. In the Canterbury region, recent years have seen widespread conversion of dryland sheep and cattle grazing, to a more intensive irrigated dairy farming. To determine the effects of these land uses on soil physical properties sampling was carried out at 0-10 cm, 10-20 cm and 20-30 cm depths on the Lincoln University Dairy Farm (DF), a nearby dryland sheep grazed site (SF) and a neighbouring control site (CS), (n= 45 for each site). The three sites were located on the same Templeton soil, with the same climate, except for irrigation input. Soil properties measured were: macroporosity, bulk density, water holding capacity (WHC) at -10 kPa, -40 kPa and -100 kPa, soil particle size and soil carbon.

Macroporosity was significantly affected by irrigation and treading. Values for the 0-30 cm increment were significantly lower ($p < 0.05$) for the DF (8.8 ± 0.6%) than both SF (19.3 ± 0.6%) and CS (14.8 ± 0.9%). Within each site there was also a significant increase with each 10cm depth increment, apart from on the SF for the 10-20 cm and 20-30 cm increments and notably on the DF for the 0-10 cm and 10-20 cm increments where values were similar. This indicated effects of compaction to a greater depth on the DF. These differences in macroporosity meant that soil water content at -10 kPa, -40 kPa and -100 kPa was higher at the DF than the SF and CS. Differences were solely from the differences in macroporosity between sites and not the result of changes in the quantity of the storage pores between these matric potentials. Therfore, no significant difference was measured in plant readily available water (RAW, -10 kPa to -40 kPa, and RAW, -10 kPa to -100 kPa) between the sites. However, at -100 kPa the DF was found to have a significantly higher ($p < 0.05$) volumetric water content (θ) for the 0-30 cm increment (31.7 ± 1.1%) than both the SF (23.7 ± 1.3%) and CS (25.6 ± 1.4%). This indicated an increase in the number of pores ≤ 3 μm in diameter (at suctions greater than -100 kPa) which were not tested in this study.

These findings were in agreement with other studies comparing the effect of irrigation and grazing. In these studies irrigated dairy treatments also had similar values for RAW as dryland and sheep grazed sites but had significantly lower values for macroporosity and higher amounts of water held in pores ≤ 3 µm in diameter.

Results for soil carbon were compared as total C, C density and C storage and there were no significant differences ($p > 0.05$) between sites for any of these measurements. This finding was similar to that of another study, carried out on the LUDF and a control site in 2012, where the C storage was slightly higher on the LUDF than the control site. Further research is suggested in an additional 5-10 years to determine whether a stable state of C storage has been reached.

The results for the macroporosity, bulk density and soil carbon were analysed using target ranges for soil quality and using the soil natural capital framework. Macroporosity was found to be a more sensitive indicator for the effects of compaction on soil than bulk density. Furthermore, the soil natural capital framework was found to be a more holistic method for evaluating the state of the soil physical resource than the target ranges, established for soil quality assessment, alone. Use of the natural capital framework allowed changes in soil properties with time to be taken into account. It also allowed changes to these soil properties to be considered in terms of the ecosystem services that might be affected and human physiological needs that might not be met.

Keywords: Soil physical properties, intensification, macroporosity, bulk density, water holding capacity, carbon, storage, soil quality, natural capital

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Chapter 1

Introduction

Historically sheep farming has formed the basis of New Zealand's agricultural economy. Alongside the diversification of the NZ dairy export market, with notable increases in exports to the Chinese market and the introduction of the Middle East and Southeast Asian markets, since the 1980s dairy farming has become more profitable than sheep (Statistics New Zealand, 2013). According to Statistics New Zealand (2012) there has been a decrease in sheep numbers from 69M in 1980 to 31M in 2012. Correspondingly dairy cow numbers have increased from 2.96M in 1980 to 6.4 M in 2012. In addition irrigated areas, to largely support dairy and arable cropping, are expected to increase by a further 340,000 ha to allow for continued growth in the sectors (Carrick, *et al.*, 2013). The change in land use from dryland sheep and beef to irrigated dairy farming resulted in an increase in production revenue of $6028/ha (Ministry of Primary Industries, 2010). However, this land-use change to increased dairy farming and demand for increased production on the farm has led to an intensification in land management inputs through increases in irrigation, fertiliser use and stocking rates (Ministry for the Environment, 2007; Sparling & Schipper, 2004).

Sustainable land use practices are required to ensure that future landowners are able to produce from the land (Waikato Regional Council, 2014). In New Zealand the Resource Management Act (RMA) promotes the sustainable management of natural and physical resources. The RMA requires people carrying out activities on the land to avoid, remedy or mitigate any of the activity's adverse effects (Ministry for the Environment, 2014). The effects-based approach of the RMA means monitoring of resources and reporting on them, with State of the Environment (SoE) reporting required to determine if effects are negative. In 1998 the Ministry for the Environment further specified the need for soil quality indicators to be included in SoE reporting. Soil quality is a measure of the capability of a soil to meet the requirements of the current land use, and whether or not current practices are having adverse effects, and therefore if the practice is sustainable (Waikato Regional Council, 2014). The term soil quality is often referred to as soil health although they are slightly different with soil quality looking at management and plant productivity while soil health looks at sustainability through biological indicators (Doran & Zeiss, 2000). To evaluate the effects of land use practices on soil quality a national study was carried out from 1998-2001 by a number of regional councils across the country. The study was commonly referred to as the "500 soils project" and data collected was used to determine limits for a total of 7 chemical, biological and physical soil quality indicators for the National Soil Quality Programme (NSQP)(Sparling & Schipper, 2002). These soil indicators can then be assessed in relation to the limits set by the NSQP to determine soil quality in ongoing SoE reporting (Lambie, 2013; Sparling*, et al.*, 2004).

Analysis of the services provided by ecosystems has becoming increasingly important since the 1960s as attempts have been made towards sustainable development (Dominati*, et al.*, 2010). The concept of ecosystem services can also be applied to soils. Soils are referred to as a stock of properties or natural capital which yield a flow of valuable ecosystem goods or services into the future. Both soil quality and natural capital are similar in that they use soil indicators and parameters to determine the state or function of a soil system. However in order to accurately determine whether sustainable use of the soil resource is occurring a range of factors, besides soil indicators, must be considered. Soil forming processes are constantly changing soil properties (indicators), with anthropogenic and natural external drivers both affecting the soil forming processes, the products and services soils provide and the human needs provided by soil ecosystem services. A framework can be used to link soil natural capital and ecosystem services through the above components alongside soil properties and provides a more holistic and broad analysis of the soil resource than that of soil quality or health (Dominati*, et al.*, 2010).

When evaluating soil natural capital soil properties are separated into inherent, derived from soil formation conditions, and manageable properties. Examples of inherent properties include slope, depth, cation exchange capacity and clay types while manageable properties include macroporosity, organic matter, mineral nitrogen and soluble phosphate. Manageable properties are identified as having more practical importance as farmers and other land managers can manipulate them to optimise land use. Of the manageable properties macroporosity has been identified as the key physical attribute. When analysing macroporosity from the holistic framework approach it is found to determine water flow, solute transport and drainage through soil and as a result macroporosity influences ecosystem services such as flood mitigation and filtering of nutrients (Dominati*, et al.*, 2010; Robinson*, et al.*, 2012; Vogel & Roth, 2001). Macroporosity and associated soil physical properties therefore provide important services and it would be beneficial for land managers to be aware of the potential to change these properties and the ecosystem services they provide. Establishing a framework for evaluating soil natural capital and ecosystem services is important in providing land managers and policy makers with internationally recognised indicators, measurement methods and protocols. This allows them to assess if actual land use is aligned with governing policies and sustainability principles and allow for comparison on both national and international scales (Robinson*, et al.*, 2012).

In New Zealand, in response to increased scrutiny of the country's 'clean green' image and public demands for increased sustainability, the government established initiatives such as the Land and Water Forum in 2009 to produce the National Policy Statement (NPS) for Freshwater Management 2011 (Land and Water Forum, 2014). This NPS has directed regional councils to produce more specific plans detailing regional rules for land and water (Ministry for the Environment, 2013). The recent Land and Water Regional Plan (LWRP) by Environment Canterbury and the One Plan by Horizons Regional Council are examples. The councils have set requirements that land owners must fulfil in order to continue carrying out their activity. Under the LWRP, farmers in Canterbury must apply for resource consents if their nitrogen losses are above threshold limits for different zones and catchments. A farm environment management plan (FEMP) must accompany resource consent applications (Environment Canterbury, 2014). The purpose of the FEMP is to evaluate the nutrient, soil, water, effluent and wetland management on the farm (Irrigation New Zealand, 2014). The FEMP then identifies the impact of farm practices on the natural resources and what steps can be taken to reduce any negative ones. Understanding the effect of land management practices on soil properties is an important aspect of producing a FEMP as changes to these properties can also affect the nutrient and water management components of the FEMP and the sustainability of the farm's operation. FEMPs could be considered an evaluation of the soil natural capital and related ecosystem services on a farm scale with feedback loops to adjust farm management and the potential to advise policy in the future when plans are evaluated alongside resource consents.

Aside from the use of soil physical properties as one of the main indicators of overall soil quality they influence a range of system processes and changes in their state therefore have follow on effects. They determine infiltration rate, hydraulic conductivity and water storage which determine the moisture retention curve and therefore the necessity for irrigation to avoid a soil water deficit and decrease in crop production (Hawke*, et al.*, 2001). Porosity and soil moisture are also responsible for loss of nutrients such as nitrogen, phosphorus and sediments from the profile. Furthermore porosity and bulk density are central to the structure which allows interaction between plants, soil, water and microbes (Curran Cournane, 2010). The effect of compaction on these properties can be reduced porosity and anaerobic conditions leading to production of nitrous oxide via denitrification (Balaine, 2012).

Maybe link to some of the irrigators claims on websites that irrigation improves the soil physical health and water holding capacity.

This study involved soil sampling at three adjacent sites on the same soil type, but with different land use intensities: 1) Mowed grassland site, with no fertiliser, irrigation, or grazing history; 2) Dryland sheep farm, with no fertiliser or irrigation; 3) Irrigated dairy, with regular fertiliser and irrigation. Evaluation of soil carbon and key physical properties was carried out.

The objective of this study was to determine the effect of land use intensification on the soil physical natural capital of a silt loam topsoil in Canterbury. This information can inform our understanding of the change in soil natural capital and therefore the ensuing ecosystem services based around the physical attributes: porosity and as a result bulk density, water holding capacity and soil carbon that results from intensification, and hence the sustainability of the specific practices involved. Practices and plans can then be designed to address identified changes in soil physical natural capital.

Chapter 2

Literature review

2.1 The effect of land use intensification on soil physical natural capital

This literature review will focus on the effects of land use intensification, as seen by the increased irrigation, fertilisation and stocking rate on soil physical natural capital. The importance of porosity in natural capital and its interaction with the soil properties bulk density, water holding capacity and soil carbon has been suggested. The effect of land use intensification, at times separated into the factors irrigation and stocking rate, will be discussed in relation to these properties and the soil pore network. Due to limited research in this area, both New Zealand and international studies will be examined. The aim is to synthesise existing knowledge of effects on New Zealand soil and determine if consistent patterns exist.

2.2 Total soil carbon content

Total Carbon (C) is a measure the amount of carbon a soil contains, including inorganic (carbonates) and organic C. In NZ soils contain only small amounts of inorganic C and therefore organic C provides a good representation of total C and therefore the amount of soil organic matter C in the soil. Total C is a soil natural capital indicator and influences soil physical properties such as porosity and bulk density by providing additional structure to the soil. It is also a vital component in soil fertility, water-holding capacity, and nutrient supply to plants and microorganisms. Total C is generally measured using high temperature combustion, whereby the soil is combusted and the carbon dioxide released is quantified using infrared. There are not upper limits placed on total C for soil quality purposes, the more organic matter present the better. Lower limits have been established for the 0-10 cm depth, which is the standard depth used for soil quality measurements, for each Soil Order: Organic soils no lower limit as assumed to contain more than 18% by definition, Allophanic soils 3%, Recent, Semiarid and Pumice soils 2% and all other orders 2.5% (Lambie, 2013).

Although there is literature analysing the effect of irrigation on a range of chemical properties, including soil pH and nitrogen, this review will focus on soil organic carbon (SOC) owing to its effect on soil physical properties such as bulk density, soil aggregation and, as a result, soil water holding capacity. Most studies have found that irrigation does have an impact on SOC, however, the size of the effect (increase or decrease), and magnitude depend on the initial SOC levels, annual rainfall and time under irrigation, amongst other factors.

Working in two semi-arid environments Blanco-Canqui, *et al.* (2010) found that the response of SOC concentration to irrigation varied for the sites. The site with the higher baseline irrigation treatment (127 mm) had a 30% increase in SOC in the 5-10cm horizon when irrigation was increased to 254 mm. While the site with the lower baseline irrigation (66 mm) had a 46% increase in SOC throughout the 0-10 cm horizon when irrigation rates were increased to 217 mm. Similarly, a review by Trost, *et al.* (2013) compared the change in SOC for a range of studies in both Arid and Semi-arid regions and found that soils with a higher initial SOC showed less of an increase in SOC content with increased irrigation than those with a low initial SOC. They suggested that the reason for this was that soils with higher initial SOC had higher microbial levels than those with low initial SOC. The high numbers of microbes meant that additional OM inputs were quickly decomposed so that the high initial SOC soils did not see an increase in SOC with irrigation. The finding suggests that SOC levels are largely influenced by the size of the microbial population available to utilise SOC inputs.

In New Zealand, the effect of irrigation was studied by Rickard & Cossens (1968) in Central Otago on Semi- arid, sub humid and humid climates in the Clutha Valley corresponding to Semi-arid, Pallic, and Brown soil orders in the New Zealand Soil Classification (Hewitt, 2010). Semi-arid soils are known for their weak weathering, poor structure, and accumulation of carbonate in the subsoil. Pallic soils have weak structure and a high density while the coatings of iron oxides in Brown soils provides a strong structure and moderate bulk density (Landcare Research, 2014c). Under irrigation, SOC was found to increase in Semi-arid and Pallic soils (from 1.9% to 2.3% and from 2.4% to 3.3% respectively), but decrease in Brown soils (from 3% to 2%).

These results are consistent with those of Trost, *et al*. (2013) and a similar hypothesis could be applied here. Soils in higher rainfall regions typically have higher initial OM and therefore SOC. As a result these soils are able to sustain a higher population of soil microbes and this leads to an increase in decomposition of OM, offsetting any increase in SOC from increased biomass production under irrigation. Other studies support this, where Arid or Semi-arid land with low fertiliy, low initial ogranic matter and low rainfall, all recorded increases in SOC with irrigation (Blanco-Canqui*, et al.*, 2010; Bordovsky*, et al.*, 1999; Singh*, et al.*, 2013).

A study on the Lincoln University Diary Farm (LUDF) showed that differences in SOC between sites depended on the method of analysis (West, 2012). Two sites were compared, an irrigated, fertilised dairy farm and an undeveloped control site. Measurements were taken at intervals to a total depth of 80cm. C content (% of SOC in the sample analysed) declined with depth for both sites with significant differences seen only in the lower horizons. The dairy farm had significantly lower C content than the control site at 30 – 40 cm (0.7 ± 0.3 versus 1.5 ± %) and 40 – 60 cm (0.4 ± 0.1 versus 0.8 ± 0.4%). Carbon density is a product of C content and bulk density. In comparison to C content, when comparing C density values, the dairy farm had significantly higher values at depths 0 – 5 cm, 5 – 10 cm, 10 – 15cm and 15 – 20 as shown in Figure 2.1. A final method called an equivalent mass method was used to determine C storage. Soil bulk density measurements at each increment (kg m^3) were adjusted to masses by multiplying by the depth of the increment (m). This mass was then multiplied by the C content % to give the mass of C for a known mass of soil (kg C/ m^2). Figure 2.1 shows that based on equivalent mass the C storage was significantly higher at the dairy farm than the control site to depths of 15 cm, 20 cm and 30 cm only. These results indicate that the effect of irrigation on the mass of SOC at the dairy farm site was limited to the 0-30 cm depth

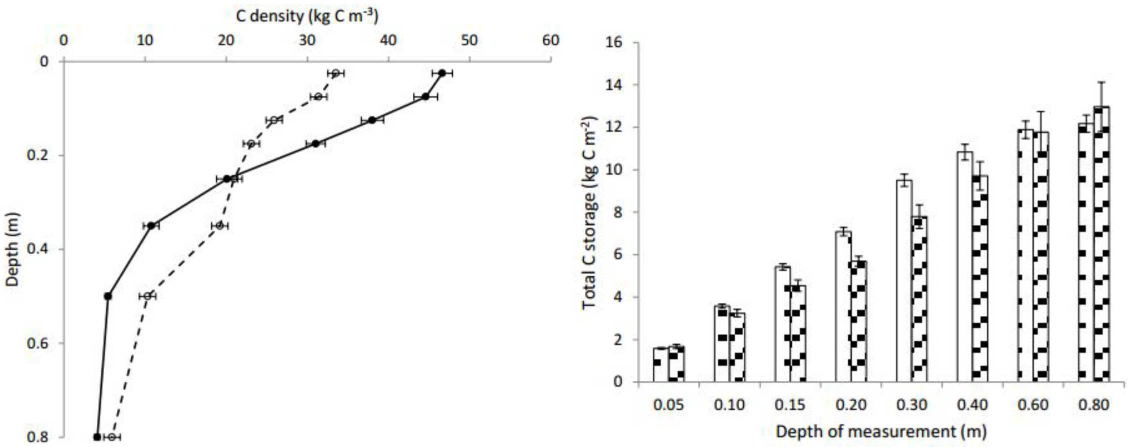


Figure 2.1 Methods of C analysis: Left, C density (kg C/m3) dairy farm (solid line) control site (dashed line). Right, total C storage using the equivalent mass method (kg C/m2) dairy farm (dots) and control site (angled line) (West, 2012).

Using the data collected in the “500 soils project” alongside additional data sets a study was carried out by Sparling & Schipper (2002) to evaluate the contribution of land use and soil type to the variability in soil properties in order to assess overall soil quality and complete State of the Environment (SoE)reporting on a regional scale. They found that the majority of variability in total C was due to soil type rather than land use with values ranging from 8-154 Mg/ha. While there were few significant differences between land uses there was a tendency for total C to be higher under pastures and indigenous vegetation than cropland and plantation forests. Testing the effects of different land uses on the same soil type Sparling, *et al.* (2000) found that Total C was significantly higher under indigenous forest than pasture for one of the soils tested while other results trended similarly but were not significant, findings were not further broken down to present changes under dairy or dryland alone.

2.3 Bulk density

Bulk density is a measure of the ratio of the mass of soil to the total volume of soil. It can give an indication of porosity or compaction (McLaren & Cameron, 1996). Increases in bulk density can result in loss in aeration and drainage, negatively impacting plant growth. In contrast soils with low bulk density are loosely packed, can be susceptible to erosion and often suffer from insufficient water reserves for good agricultural production (Sparling, *et al.*, 2008). Bulk density is measured using intact cores which are dried at 105°C and the dry weight of the soil per unit volume of the core calculated and usually expressed as Mg m^{-3} or g cm^{-3} (McLaren & Cameron, 1996)(g cm^{-3} will be used in this study).

Bulk density values at which plant productivity is reduced have been defined to identify target ranges for soil quality assessment. Ranges are influenced by soil organic matter and mineralogy, with target ranges for 5 soil orders shown in Table 2.1 (Sparling, *et al.*, 2008).

Table 2.1 Target ranges for bulk density for 5 soil orders (Sparling, et al., 2008)

Soil order	Bulk density target range (g cm^{-3})
Semiarid, Pallic & Recent Soils	0.7–1.4
Allophanic Soils	0.5-1.3
Organic Soils	0.2–1.0
Pumice & Podzol soils	0.6–1.4
All other soils	0.6–1.4

Singer & Munns (1991) note that 50% porosity is satisfactory for plant growth. With particle density of 2.65 g cm^{-3} typical for Canterbury soils formed from greywacke parent material, a soil with a porosity of 50% would have a bulk density of 1.32 g cm^{-3} which is in agreement with the target ranges suggested by (Sparling, *et al.*, 2008). Studies examining the effect of irrigation on bulk density have found that irrigated soils have higher bulk densities than undeveloped soils (Rickard & Cossens, 1968). In comparison Singh, *et al.*, (2013) reported that irrigation reduced bulk density by 5.3-6.6% and that bulk densities were highest for the treatments that had the least irrigation applied.
In a semi- arid climate on the Texas Plains, bulk density of a sandy soil was found to be higher under dryland treatment than irrigation (Bordovsky, *et al.*, 1999). This was thought to be because irrigation increased OM residue, which was slowly incorporated into the soil, decreasing bulk density. In the

semi- arid, sub humid and humid environments in Otago, bulk density was found to increase with irrigation, as shown in Table 2.2, for all soil types, Semi-arid, Pallic and Brown (Rickard & Cossens, 1968).

Table 2.2 Change in bulk density (Mg m^{-3}) of three soil types with irrigation (Rickard & Cossens, 1968)

Soil order	Unirrigated bulk density (gcm^{-3})	Irrigated bulk density (gcm^{-3})
Semi-arid	1.1-1.7	1.2-1.6
Pallic	1.0-1.5	1.1-1.6
Brown	0.7-1.4	1.0-1.5

Overall studies were inconclusive on the effects of irrigation alone on bulk density and found that other factors such as cropping sequence (Singh*, et al.*, 2013) and stocking rate (Houlbrooke*, et al.*, 2009) had significant impacts.

Li et al (2014), in a study of a vineyard in an arid climate in China, found that bulk density was less in the 20-40 cm horizon (1.5 g cm^{-3}) than the 0-20 cm horizon (1.6 g cm^{-3}) as a result of increased trampling on the surface and high root density in 20-40 cm increment. In this study soil moisture was negatively correlated with bulk density: as soil moisture increased bulk density decreased.

In North Otago, in a semi-arid climate, higher bulk density was measured under irrigation than dryland treatments (Houlbrooke*, et al.*, 2009). The effect of stock in this study was also noted: greater compaction and increased bulk density of the topsoil profile was found under cattle grazing than sheep. West (2012) in sub-humid Canterbury showed an inverse linear relationship between C content and bulk density; as SOC content increased bulk density decreased. The study showed that bulk density was higher on the irrigated dairy farm than the non-irrigated control site.

Comparing the impact of dairy and sheep grazing Drewry, *et al.* (2000) found that there was no significant difference between farm type on the mean bulk density of a range of soil types at any depth however bulk density increased between 0 – 5 cm and 5 – 10 cm by a greater amount for the dairy farms (0.16 Mg m^{-3}) than for sheep farms (0.12 Mg m^{-3}; SED 0.01; $P<0.01$). The study concluded that, when changes in macroporosity, bulk density, and air permeability over all soil depths were analysed, soils on dairy farms were significantly more compact than those on sheep farms.

2.4 Soil aggregates

Soil aggregates are forms of soil peds and can be formed through both natural and human activities (McLaren & Cameron, 1996). When evaluating soil natural capital and quality, aggregate stability is used as an indicator. Aggregate stability refers to the ability of soil aggregates to resist disruption when outside forces (for instance cultivation or stock treading) are applied. It is commonly measured on soils used for cropping (AgResearch, 2013). Tardieu, *et al.* (1992) found that a loose assemblage of aggregates between 0.35 – 0.12 mm allows unimpeded root growth and root access to air, water and nutrients, while decreased aggregate size may increase P leaching risk. The increase or decline of macroaggregates (> 0.25 mm diameter) and microaggregates (0.05-0.25 mm diameter) is found to be affected by irrigation in a number of studies.

A study carried out in Kansas by Blanco-Canqui, *et al.*(2010) on a Semi-arid soil found that the proportion of macroaggregates increased whereas microaggregates declined with irrigation (particularly in the 5 - 10 cm depth). They noted that aggregate size and stability increased with an increase in SOC concentration. Because SOC content in the soil increased with irrigation, the study suggests that irrigation can result in structural development and reduced erosion. Singh, *et al.* (2013) found an increase in micro over macroaggregates with irrigation (although both are elevated), which they attributed to increased root biomass and crop residue. Despite the emphasis on microaggregation in their study, they too concluded that increased irrigation, and the increase in root biomass and crop residue that resulted, was the cause of the increased number of aggregates.

The review of literature carried out by Trost, *et al.* (2013) considered all findings surrounding soil aggregation. Some of the studies reviewed showed that wetting and drying cycles due to irrigation had a negative impact on the stability of macroaggregates. However, others showed that these cycles led to an increase in water stable aggregates greater than 5 mm diameter and a decrease in those less than 5 mm. Velocity of moisture infiltration was also a factor, with rapid infiltration leading to disaggregation. Finally rain and sprinkler irrigation droplets can increase aggregate breakdown from their impact on soil surface.

In terms of New Zealand studies the study conducted on a Pallic soil in the sub-humid climate in north Otago used a structural condition score (SCS) to quantify soil structure (Houlbrooke*, et al.*, 2009). Scores were determined by breaking up soil onto a tray and judging on visual assessment of the size, shape, and porosity of aggregates, and their cohesion and root development. There was not found to be any significant difference in SCS as a result of grazing intensity, between the cattle grazed treatments (irrigated or dryland) and the sheep grazed treatments (irrigated or dryland). However there was a significant difference in SCS as a result of irrigation, between irrigated and dryland treatments. For example the average SCS for the irrigated cattle treatment from 2005-2007 was 1.6 ± 0.4 (± LSD, P = 0.05) which was significantly lower than the dryland average for the same time period (2.1 ± 0.4). This indicates greater soil compaction (lower macroporosity and higher bulk density) under irrigation. Although grazing intensity, changing from sheep to cattle, did not have a significant effect on aggregate stability it is still an important factor in the study as other research has shown that it is the combined effect of irrigation and grazing which impacts soil properties (Drewry*, et al.*, 2008).

A soil quality indicator report produced by AgResearch (2013) noted that an interdependent interaction between aggregate stability, macroporostiy and total C was expected to be seen in trials. However, while there was a significant correlation between aggregate stability and total C there was no relationship between aggregate stability and macroporosity. This was concluded to be because those sites with low macroporosities were under animal grazing. Even if the soils at these sites had high levels of total C and good aggregate stability they would still become compacted under the grazing pressure. Thus, it was determined that aggregate stability was not a useful indicator of compaction.

Results for aggregate formation are similar to results obtained for bulk density and SOC in that there is a range of responses in the published studies. There are also a number of factors that influence response, such as: whether or not the site was grazed, the type of irrigation used and how quickly irrigation water infiltrates the profile.

2.5 Porosity

Porosity is described as the key physical natural capital indicator by Dominati, *et al.*(2010) due to its influence on soil water storage, air permeability, gaseous diffusion, drainage, root penetration and habitat for soil organisms. The NSQP also identified it as an indicator for soil quality. McLaren & Cameron (1996) define porosity (ε) as the ratio of the volume of pores to the volume of soil. Typical values for porosity range from 30% to 60% and porosity is inversely related to bulk density. Porosity is calculated from dry bulk density (ρ_b) and average particle density (ρ_p) of the soil. Total porosity can be separated into different fractions based on pore size: macropores and micropores as shown in Table 2.3 in order of decreasing pore size**.**

Table 2.3 Classification of pores according to size and function, based on (McLaren & Cameron, 1996).

	Pore description	Pore diameter (µm)
Macropore	Air pores	> 300
	Transmission pores	300-30
Micropore	Storage pores	30-0.2
	Residual pores	<0.2

The pore size distribution determines the water holding capacity (WHC) and therefore availability of water to the plant. It also determines the drainage or hydraulic conductivity of the soil, the speed at which water drains from the profile (mm/h). Figure 2.2 shows how WHC and hydraulic conductivity change with soil type as a result of the different distributions of pore sizes. For instance Figure 2.2 shows that sand has a low WHC because it is comprised of high quantities of macropores (drained at -5 kPa) and air capacity pores (drained at -10 kPa) in comparison to silt and clay dominated soils. The smaller the pores the more suction or tension (also known as matric potential) is required to withdraw water from the soil. Matric potential is typically expressed as kPa, although a range of units are used in literature, with a negative value to show that energy must be exerted to extract water from the soil. Plants are able to take up water held at a matric potential of -10 kPa (FC) to a potential of -1500 kPa also known as permanent wilting point (PWP). The water held between FC and PWP is termed the available-water capacity (AWC) however as the soil moisture reaches PWP it becomes more difficult for plants to absorb water and growth can be limited. Another measure is readily available water (RAW) which in New Zealand is often defined as the proportion of the soil water drained between -10 kPa (FC) and -100 kPa (McQueen, 1993). This range is important because -100 kPa is found to be the stress point for grasses, as at higher matric potentials soil water becomes more difficult to extract and they are unable to maintain maximum pasture production (McLaren & Cameron, 1996). Stress point is an important soil property as it is used as the trigger point for scheduling irrigation applications before crop growth starts to be limited by soil water availability. At PWP only water held in the micropores remains, this water is unavailable to plants.

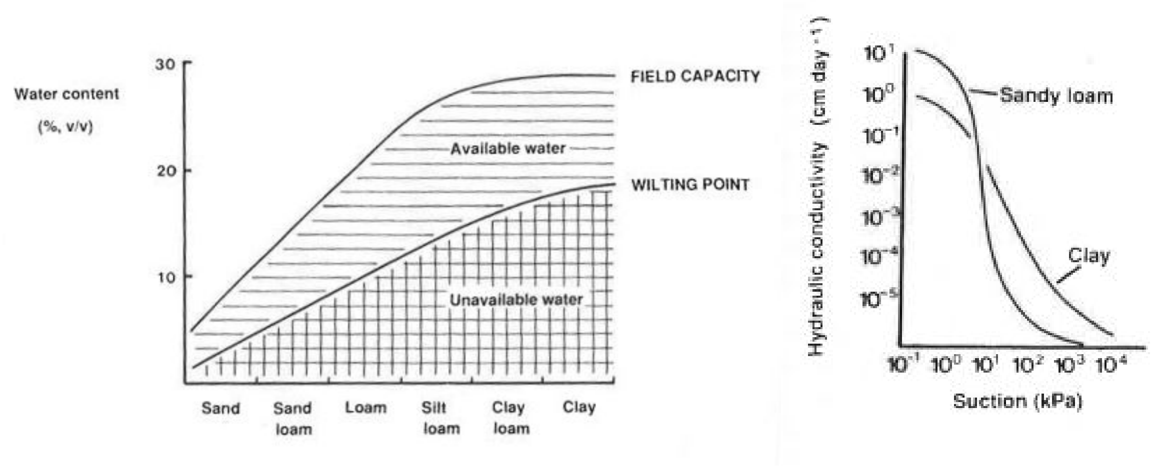


Figure 2.2 Left, relationship between soil texture and soil water content at field capacity, and permanent wilting point. Right, relationship between hydraulic conductivity and suction (matric potential) for a clay soil and a sandy loam (McLaren & Cameron, 1996).

Disturbances to soil physical properties such as compaction may change the pore size distribution and consequently the WHC. This is because compaction alters soil total porosity and the relative volume of large and small pores which decrease and increase respectively. At any given matric potential soil pores up to a fixed diameter are water filled and any larger pores are air-filled. Soil compaction has been reported on by Assouline (2006), using relationships between water retention models and bulk density, and was found to reduce the proportion of larger pores and increase the proportion of small pores. The result on the range of soils, sands silts and clays, studied was a net increase in water retention. However this method of evaluating the effect of compaction on physical properties was described as limited. Other studies such as by Lambie (2013) have found that macroporosity is generally a more sensitive measure of compaction than total porosity and bulk density because macropores are the dominant pores responsible for aeration and drainage and are preferentially destroyed by compaction.

2.5.1 Macroporosity

Macropores generally represent space around soil aggregates and are usually air filled, containing water for only short periods. Macropores must be drained for optimum plant growth. In comparison micropores are responsible for water storage in soil and are usually found within, rather than between, soil aggregates. Macroporosity (also termed air filled porosity) determines the movement of water and gases in soils, influences heat exchange, root growth and distribution, as well as nutrient uptake processes. Macropores also provide habitat for a range of species. Low macroporosity means reduced soil aeration and drainage and a reduction in surface water infiltration and drainage leading to increased surface run-off. Extended water-logged conditions due to low macroporosity also lead to an increase in gaseous losses of C (increased methane emissions) and N (nitrous oxide emissions), and less root and plant growth. Therefore macroporosity is a useful indicator to assess changes in soil physical condition under different land-uses including pasture, cropping horticulture and forestry (AgResearch, 2013).

The pore size definition (minimum pore diameter in µm) for a macropore varies across literature with authors such as McLaren & Cameron (1996) and Drewry, *et al.* (2004) defining 30 µm as the limit while McQueen (1993) used 60 µm and others such as Koppi, *et al.* (1992) use various larger diameters for instance 195 µm. As a result various studies define different matric potential requirements for drainage of macropores. Drewry, *et al.* (2004) suggest -10 kPa while McQueen (1993) suggests -5 kPa with FC reached by -10kPa. When comparing macroporosity across literature it is important to note the pore size diameters employed (Drewry, *et al.*, 2008).

There is also a range of definitions for the macroporosity or air filled porosity at which plant growth becomes limited (Drewry, *et al.*, 2008; Sparling, *et al.*, 2008). Sparling, *et al.* (2008) indicate target ranges as 6-30 v/v% for pasture, cropping and horticulture and 8-30 v/v% for forestry. Drewry, *et al.* (2008) summarise findings from a range of studies and explain that the critical level of air filled porosity depends on the crop grown and the temperature and microbial activity (higher temperatures and microbial activities require higher levels of air filled porosity). However a threshold of 10% macroporosity (at -10 kPa), below which plant growth starts to become limited, appears to be favoured by the majority of studies.

In their review of studies analysing the response of soil properties to compaction Drewry, *et al.* (2008) define compaction of soil as occurring when the soil is unsaturated involving a decrease in the volume of large inter-aggregate pores, while consolidation is the compression of a saturated soil after compaction has occurred, it is comparatively slow as the viscosity of water is much greater than air. Poaching is used to describe the effect of stock trampling on very wet soil (often as a result of winter-grazed systems) while pugging results in deep hoofprints. The review reported that findings from a range of studies had shown macroporosity (pores >30 µm) decreased when grazed by cattle even if for relatively short interval. One of the studies reviewed showed that a silt loam irrigated to near saturation and then stocked with 450 cows/ha for 1.5 hours had a 29% decline in macroporosity (pores >30 µm) for the 0-50 mm soil depth (Menneer, *et al.*, 2005). The review also found that saturated hydraulic conductivity (mm/h) was reduced by 80% at a depth of 50-100 mm in areas where pugging had occurred on soils near saturation. Similarly infiltration rates (rate at which water can enter the soil surface) were reduced by 98% for high stocking rates in comparison to low rates (specific rates were not given). Both Drewry, *et al.* (2008) and Houlbrooke & Laurenson (2013) suggest that the compaction effect of grazing on the soil increases in relation to moisture content until soils reach plasticity, where the water held within the soil reduces the compression of the void space.

However, effects are not limited to soils with soil water levels near saturation and the review by Drewry, *et al.* (2008) reports on findings where infiltration rate (mm/h) at a soil moisture of 25% decreased by a substantial 49% under a low stocking rate of 2.7 ha/ animal unit/ yr (1 animal unit is a 1000 kg cow). Macroporosity values (pores >30 µm) also decreased under dry conditions by 61% at a stocking rate of 2 cows/ha for the 0-100 mm soil depth. In a separate study conducted by Sparling & Schipper (2002), reviewing data collected as part of the NSQP, found that there was a substantial number of samples taken from soils under mixed cropping, horticulture and pastures for dairy and drystock production that had macroporosity (pores >30 µm) values of < 10%.

Houlbrooke & Laurenson (2013) carried out a study to test the effect of irrigation (irrigated versus dryland) and stock (cattle versus sheep) on soil porosity. They found that total soil porosity from 0-30 cm depth was less in soils grazed by cattle (45.9% with irrigation and 48.6% for the dryland treatment) relative to sheep (50.6% and 49.9% respectively) but not significantly different between cattle irrigated and cattle dryland treatments. Changes in macroporosity due to irrigation were greatest under cattle irrigated treatments (10.4 ± 3.5% LSD), with a 35% decrease from dryland cattle treatments (18.4 ± 3.5%). Because of the decrease in macroporosity and increase in microporosity it was hypothesized that there would be an increase in soil water content at FC however no increase was observed for any of the treatments. This was suggested to have been because of the corresponding decline in total porosity. For example despite an increase in microporosity for the 0-10 cm increment from dryland sheep (36.8 ± 4.4%) to irrigated dairy (39.0 ± 4.4%) there was no increase in water at FC because total porosity also decreased (55.2 ± 3.3% to 49.3 ± 3.3% respectively). However soil water content at PWP was significantly greater in the cattle irrigated plots relative to the other treatments and corresponded to a significant reduction in AWC (water held between FC and PWP) for the 0-30 cm increment.

In this study water content at trigger point, defined as -100 kPa, with water held in pores smaller than 3 µm in diameter, were most affected by treading damage. As a result readily available water (RAW defined as the water held between FC and -100 kPa) was significantly lower for the irrigated cattle plots relative to cattle dryland and all sheep grazed plots. Interestingly it was noted that this decrease in RAW means that irrigation will need to be applied more regularly for shorter periods to replenish water to FC. Futhermore, the reduction in macroporosity was expected to lower infiltration rate meaning that surface runoff could be triggered more frequently. There was also expected to be a change in the critical moisture content (CMC), the point at which the greatest level of soil compaction occurs and therefore that most undesirable for grazing. Because of the decrease in RAW with compaction, the CMC could be reached at lower pressures and could persist for a longer time. This is turn could lead to subsequent grazing events having an even more detrimental effect on soil porosity.

Houlbrooke & Laurenson (2013) also state that the effects of animal treading were limited to the top 20 cm of the soil profile while Drewry, *et al.* (2000) found that there was no evidence that macroporosity changed with depth beyond 5-10 cm. In the same study Drewry, *et al.* (2000) found that, while there was no significant difference in macroporosity between sheep and dairy farms at sampled depths, the decrease in mean macroporosity between 0-5 cm and 5-10 cm on the dairy farm (3.6%) was significantly more than the decrease for the same depth increments on the sheep farm (1.5%). This affect was more notable on the Orthic Gley and Fragic Pallic soils on the dairy farms than on the Brown soils which were regarded as well-structured and most likely to resist treading damage.

Finally Drewry (2006) reviews the ability of soil physical properties to recover from treading damage and found that soil physical condition would naturally recover when animals are partially or completely excluded from the pasture, although improvements were generally limited to 10-15 cm depth. As macroporosity is affected to a depth of 10-20 cm, improvements to this depth could be sufficient to recover soil macroporosity (Drewry*, et al.*, 2000; Houlbrooke & Laurenson, 2013). In southern New Zealand dairy cows are typically removed from the milking area in the winter so pasture is not grazed or treaded. Interestingly recovery of soil physical properties, including macroporosity (pores > 30 μm), was found to be less over winter than during spring and summer. Removal of cows for 4 months is suggested to be sufficient to improve physical structure, including macroporosity, when treading effects are not seen below 15 cm.

2.6 Soil water holding capacity

Information on a soil's water holding capacity (WHC) is provided by the relationship between its water content and water potential. It can be measured using tension tables to extract the water in larger pores and pressure plates, providing more powerful pressure, to extract the water in smaller pores. Central to a soil's WHC is the available water holding capacity which represents the total amount of water that could be available for plant uptake. This range is defined as -10 kPa to -1500 kPa although most plants are really only able to take up water without growth stress within the RAW range (-10 kPa to -100 kPa, described above) (McLaren & Cameron, 1996).

Li, *et al.* (2014) found that bulk density (in turn affected by porosity and SOC) and texture influenced soil water holding capacity. As bulk density increased, soil water holding capacity decreased, and as clay and silt fractions increased, soil water holding capacity increased. Both this study and that by Singh, *et al.* (2013), found that water holding capacity and soil moisture content at field capacity increased with irrigation. In agreement with these findings Rickard & Cossens (1968) stated that irrigation affects SOC, bulk density including porosity, and soil aggregates which are all properties that determine the ability of soil to retain water. They showed that changes to soil physical properties as a result of irrigation resulted in an increase in available water for the 0-30 cm depth.

Cossens & Rickard (1966) found that irrigation altered Semi-arid soils in the direction of Pallic soils; increasing field capacity, available moisture, bulk density and organic carbon while decreasing porosity. Pallic soils did not change much with irrigation. A few years later Cossens & Rickard (1969) found that irrigation altered Semi-arid soils in the direction of Pallic soils and Pallic, in turn, in the direction of Brown soils; increasing field capacity, AWC, bulk density and organic carbon while decreasing porosity. For instance the AWC of the undeveloped Semi-arid soil increased with irrigation from 57 mm (in the top 0-300 mm of the profile) to 64 mm, closer to the value of the undeveloped Pallic soil at 72 mm, which increased to 76 mm with irrigation to match the undeveloped Brown soil at 79 mm, which increased to 96 mm under irrigation. However, the effects of irrigation on physical properties of Brown soils was slightly different to Semi-arid and Pallic. AWC was the only property - out of field capacity, AWC and SOC - where there was an increase in the value for the Brown soil with irrigation. Field capacity and SOC of Brown soils showed a decrease with irrigation. In another study, Cossens & Rickard (1968) also found that available moisture was higher on the irrigated than undeveloped soils of both Semi-arid and Pallic soils.

Studies consistently found that increasing irrigation increased soils' water holding capacity. This was as a result of higher SOC levels leading to lower bulk density, increased porosity and soil aggregates. In comparison grazing is found to decrease soil water holding capacity as compaction results in a decrease in total porosity and macroporosity and an increase in PWP leading to a decrease in AWC

(Houlbrooke & Laurenson, 2013). Overall damage to soil physical properties is greatest when pasture stocking is combined with high soil moisture (Drewry*, et al.*, 2008).

2.7 Conclusions

The main conclusions of this literature review are;

- There are a range of soil physical properties which can be used as indicators of the state of soil physical natural capital and soil quality. Of the physical properties reviewed macroporosity was found to be the most useful indicator while bulk density is also important.
- Changes in soil physical properties are interrelated. For instance a decrease in SOC and porosity can lead to an increase in bulk density and in turn soil water holding capacity.
- Both irrigation and stocking have a significant effect on soil physical properties however it is the combined effect which can have the most detrimental effects and impact on soil physical natural capital.

Chapter 3

Materials and methods

3.1 Study sites

The trial was conducted at three sites which were chosen for their different land use intensities. In order of decreasing land use intensity: a fertilised, seasonally irrigated paddock on the Lincoln University Dairy Farm (DF), dryland sheep grazed farm (SF) and a 'control site' (CS), grid references for the locations are provided in Table 3.1.

Table 3.1 Grid references of the sites sampled (NZTM)

Site	Grid reference
Dairy Irrigated	E1555033 N5167961
Dryland sheep	E1556087 N5167430
Control site	E1556183 N5167303

Sampling of the DF took place on the North block of the farm in paddock N1, 15 km SW of Christchurch, New Zealand. The LUDF was converted from a dryland, minimally fertilised sheep farm to its current use in February 2001. The pasture of paddock N1 has not been renovated since conversion of the farm. The sampling site (paddock N1) was cultivated to a depth of 15-20 cm during the conversion process and sown with a mixed pasture sward including perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Paddock N1 is part of the effective milking area and is typically grazed 12 times over the milking period (August to May). Irrigation was applied at 484 mm/yr from September to April for the 2007-2012 period (Pellow*, et al.*, 2013). Refer to Appendix A for fertiliser history, a site map and soil profile picture.

The SF site was located at the JML research farm on Lincoln University. The site has been under permanent sheep grazed pasture for at least 14 years. It is not fertilised and not expected to have been affected by irrigation (Mike Kempthorne, personal communication, November 10, 2014). There is the chance that in 2000/2001 the site could have received some irrigation as overspray from irrigation applications to the adjacent paddock however this is not expected to have affected the soil at the site (White*, et al.*, 2014). Refer to Appendix A for a site map and soil profile picture.

The CS site was located at the Horticultural Research Area directly neighbouring the SF site. At the CS, the area was, to our knowledge, never grazed by farm animals, fertilised or irrigated (Warwick Mottram, personal communication, June 3, 2014). However there is a chance of some vehicle traffic through the area, as it is regularly mowed to maintain lawn cover. Sampling sites were located around trees and in locations where the chance of vehicle traffic was low, and therefore the effect on the site was not thought to be significant. Vegetation at the site is a mix of grasses. Refer to Appendix A for a site map and soil profile picture.

All three sites were chosen to be of similar soil types; a Templeton silt loam family (Landcare Research, 2014b), and classified as Typic Immature Pallic soils in the New Zealand Soil Classification (Hewitt, 2010). At the dryland site the topsoil horizon texture has been previously characterised as 57% sand and 23% clay at the surface, changing to 72% sand and 11% clay at 25cm depth (Di & Kemp, 1989). This is similar to 69% sand content at 25 cm that has been measured in an adjacent paddock close to the DF site (West, 2012). An analysis of the soil particle size distribution for the sites and depth increments was carried out and findings are presented in the results section.
Soil particle size data can also be seen in Appendix A with soil fertility results given below in Table 3.2. These sites are subject to a mean annual rainfall of ≈ 670 mm with a SD (standard deviation) of 150 mm/yr for the 2000-2010 period and an average annual evapotranspiration of 870 mm, resulting in an average annual water deficit of approximately 200 mm (SIDDC, 2007).

Table 3.2 Results from soil fertility for the dairy farm (DS), sheep farm (SF) and control site (CS) for the three depths: 0-10 cm, 10-20 cm and 20-30 cm

Soil depth (cm)	**pH**			**Base saturation (%)**			**Olsen P (mg P/L)**		
	DF	SF	CS	DF	SF	CS	DF	SF	CS
0 - 10	5.9	5.5	5.8	63.3	49	54.3	25.3	17.3	11.7
10 - 20	5.9	5.5	5.9	56	47	56.7	13.7	9.7	11.3
20 - 30	5.8	5.6	5.9	49.7	44.3	54	7.7	8.7	8.7

3.2 Experimental design

Sample collection occurred during May and June 2014. Because of high rainfall over the March to May period the soils were at field capacity during sampling. At each site soil augers were used to determine that the soil morphology (type, texture and depth of soil horizons) were consistent, both within and between sites. Sites were also selected to be 'mid-paddock', located away from high traffic areas such as gateways, water troughs, and vehicle travel paths.

At each site samples were collected at 5 m grid spacing, with a total of 15 replicate points sampled at each site. At the CS 12 replicate points were sampled using the 5 m grid spacing followed by 3 samples at random to avoid areas at the site which might have been subject to vehicle traffic. In addition, at each of the replicate points samples were taken for 3 depth intervals: 0-10 cm, 10-20 cm and 20-30 cm. For each site this resulted in a total of 45 samples. The sampling design was partially advised by West (2012) and a study carried out by Di & Kemp (1989). Coordinates of the transects were recorded for each site using a GPS (Garmin GPSmap 62s) (Appendix A)

At each point on the grid six soil cores were sampled, as well as ≈ 500 g of bulk soil collected over the same depth increments as the soil cores. Two cores (one large, 10 cm diameter by 7.5 cm depth and one small, 4.75 cm diameter by 3 cm depth) were collected at each of three depths: 0-10 cm, 10-20 cm and 20-30 cm. Cores were sampled so that they were centred midpoint of each depth increment. The large cores were used for analysis of macroporosity, drainage porosity and bulk density, small cores were used for analysis of air-filled porosity at -40 kPa and -100 kPa. Bulk soil samples were taken at each depth for soil particle size analysis and soil fertility tests.

Soil cores were collected by using a sharp knife to hand carve an undisturbed soil pedestal slightly larger than the core diameter before gently hand pressing the core down the pedestal. The sharpened front edge of the stainless core carves the excess soil from the pedestal as the core is pressed down, leaving an undisturbed soil column within the core. The core was typically carved so the top was 0.5 – 1 cm below the soil surface, to allow for surface indentations. The core top could then be sliced to an even and uniform soil surface for measurements using tension tables and pressure plates. The core base was carefully sliced off with a large spatula 1 - 2 cm below the bottom of the core and then gently hand carved with a sharp knife to an even and uniform soil surface, again flush with the base of the core.

Cores were immediately wrapped in plastic film, then carefully transported back to the laboratory using foam lined storage crates.

3.3 Soil analysis

Following collection samples were stored in a chiller at $4^{o}C$ before analysis in the laboratory. All cores were carefully trimmed with a sharp knife in the laboratory so that calculations of bulk density and θ at various pressures would be accurate. Worm activity in soil cores is known to increase when cores are placed on tension tables and creates measurement problems. In order to remove worms, cores were placed in a water bath which was heated until worms had stopped emerging from cores and had been removed. They were then placed in large plastic containers and water was added till it reached three quarters of the way up the core. They were left in these water baths for 24 hours to ensure complete saturation of all pores. Large cores were then placed on tension tables, made of a fine silica slurry over top of a layer of sand, with a hanging water column used to apply the suction. The hanging water column tube was initially lowered to 0.5 m to provide a suction equivalent to -5 kPa. Cores were left for 5 days to 1 week and were then weighed once it was certain that cores were at equilibrium. Cores were again placed on the tension tables and θ at -10 kPa was determined by lowering the attached tube to 1m, the same process was followed as for -5 kPa. Bulk density was determined by placing cores in a 105°C oven for 48 hours, subtracting the core weight from the weight of the completely dried soil.

The same process was carried out on the small cores except pressure plates were used; this is where water is forced out of the core through a porous plate by the pressure in the chamber to extract the water held in the smaller micropores. Pressure in the pressure plates was adjusted to -40 kPa and left to equilibrate until cores had stopped draining, then the cores were removed and weighed. The same process was repeated for measurement of θ at -100 kPa. Equations 1, 2 and 3, below, were used to calculate bulk density (ρ_b), total porosity (ε) and water content (θ) at the various suctions.

Equation 1

$$\rho_b\ (\mathrm{gcm^{-3}}) = \frac{\text{mass of dry soil (g)}}{\text{total volume of soil (cm}^3\text{)}}$$

Equation 2

$$\varepsilon\ (\%) = 1 - \rho_b / \rho_p$$

Where ρ_p refers to a particle density of 2.65 gcm^{-3}

Equation 3

$$\theta\ (\mathrm{gcm^{-3}}) = \frac{\text{water at suction (g)}}{\text{total volume of soil (cm}^3\text{)}}$$

For soil carbon analysis approximately 250 grams of the soil collected at each site and depth was air dried for 48 hours. All samples were then sieved (2 mm sieve) and a 0.5 ± 0.1 g sub-sample was analysed for C% and N% using an Elementar analyser (Elementar Analysensysteme GmbH, Germany). Soil particle size and fertility analysis was carried out on each depth at three points at each site giving a total of nine samples from each site and 27 over the whole trial. For particle size analysis

100 g of moist soil was sent to a laboratory for determination of sand, silt and clay content using the pipette method (Claydon, 1989)To determine soil fertility 200-300 g of air dried soil was sent to Hills laboratory for analysis.

3.4 Statistics

Data sets were statistically analysed using GenStat 16. Data normality was tested for each data set and residuals for each were found to be normally distributed. This result suggests that ANOVA is a suitable statistical analysis to perform. Two-way ANOVA was therefore carried out on each of the response variables with Site and Depth as the factors. Response variables were: bulk density, total porosity, macroporosity, total drainage porosity, water at -10 kPa, -40 kPa and -100kPa, readily available water from -10 to -40 kPa and -10 to -100 kPa, carbon concentration, carbon density and carbon storage. Outputs were given for the effect of site, depth and the combined effect of site and depth (termed site- depth interaction) on the response variable. Where statistically significant results ($P < 0.05$) were obtained, a post-hoc Tukey test was carried out to determine which Sites (DF, SF and CS), Depths (0-10 cm, 10-20 cm and 20-30 cm) or the combined Site, Depth combinations (D0-10 cm, D10-20 cm, D20-30 cm, S0-10 cm, S10-20cm, S20-30cm, C0-10cm, C10-20cm and C20-30cm) were significantly different from each other. Results from Tukey tests were displayed above the bar graphs in the results section with different letters indicating significantly different results. Confidence intervals (CI) shown as error bars on graphs are 95% CI calculated using the t-distribution for the 0-10 cm, 10-20 cm and 20-30 cm depth increments (where n = 15, Equation 4) and using the normal distribution for the complete 0- 30 cm depth (where n = 45, Equation 5).

Equation 4 **2.14 x standard error (SD/ √n)**

Where n = 15

Equation 5 **1.96 x standard error (SD/ √n)**

Where n = 45

Chapter 4

Results

4.1 Soil texture

Soil particle size, which can influence WHC and SOC, for the DF, SF and CS is presented in Figure 4.1. The distribution of particles did not change with depth within sites except for on the SF where the fine sand (0.2-0.06 mm) content increased from the 0-10 cm increment (27 ± 2%) to the 10-20 cm (29 ± 1%) to the 20-30 cm (31 ± 3%), and there was a corresponding decrease in silt (0.06-0.002 mm). Across sites the DF was found to have higher amounts of clay (< 0.002 mm) and higher amounts of silt than the SF and CS for all depth increments. For example the clay content for the 0-10 cm increment on the DF (21 ± 1%) was higher than the SF (18 ± 2%) and the CS (18 ± 1%) and the silt content for the 0-10 cm increment on the DF (61 ± 1%) was higher than on the CS (54 ± 2%), which was higher than on the SF (49 ± 1%). The fine and medium sand (0.6-0.2 mm) content on the DF was lower than on the CS, which was in turn lower than on the SF. For example, the fine and medium sand content for the 0-10 cm increment on the DF (16 ± 1% and 2 ± 1% respectively) was lower than on the CS (25 ± 2% and 3 ± 1%), which was lower than on the SF (27 ± 2% and 6 ± 1%). All sites and depths classify as silt loam texture in the New Zealand Soil Classification (Hewitt, 2010)

4.2 Bulk Density

Bulk density, a primary indicator for soil natural capital and quality, for the DF, SF and CS is presented in Figure 4.2**.** There were significant differences ($P < 0.05$) among treatments for bulk density integrated over the 0-30 cm depth (site effect). The DF had a significantly higher bulk density, 1.40 ± 0.02 gcm^{-3} (± 95% confidence interval, n = 45), than both SF (1.26 gcm^{-3} ± 0.02) and CS (1.31 ± 0.02 gcm^{-3}), while those at the CS were also significantly higher than at the SF. Bulk density was also significantly different among individual depth increments across all treatments (depth effect). Bulk density increased significantly from the 0-10 cm increment to the 10-20 cm increment across all sites. For example on the DF there was a significant increase in bulk density from the 0-10 cm increment with an average of 1.30 ± 0.03 gcm^{-3} (± 95% confidence interval, n = 15) to the 10-20 cm increment with an average bulk density of 1.40 ± 0.02 gcm^{-3}. In contrast, there were no significant differences for the site-depth interaction, for example between D 0-10 cm and S 0-10 cm.

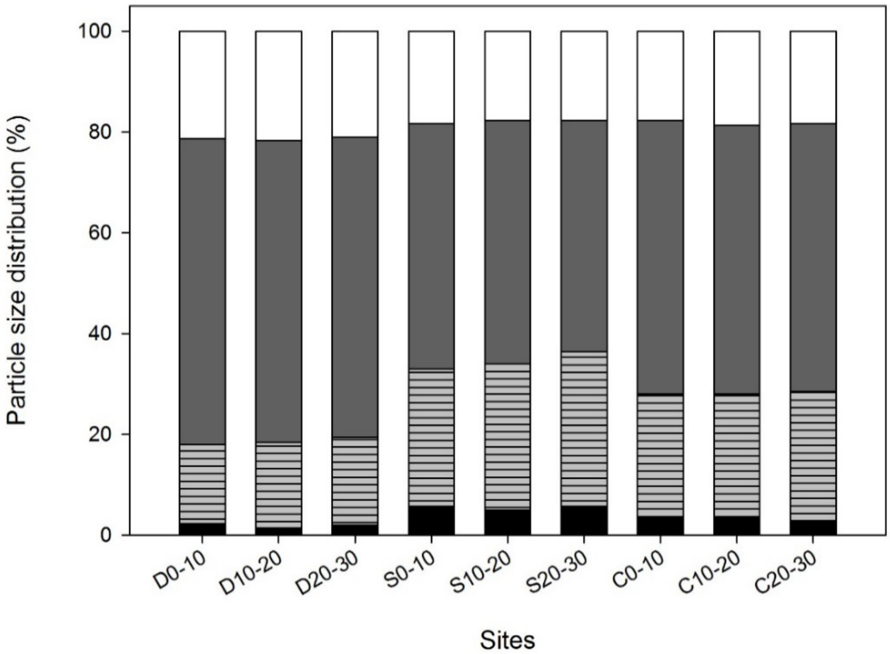


Figure 4.1 Soil particle size distribution (%) across sites and depths. Medium sand (0.6-0.2 mm, black), fine sand (0.2-0.06 mm, horizontal lines), silt (0.06-0.002, mm grey) and clay (< 0.002 mm, white). No coarse sand (2-0.6 mm) was present at any of the sites.

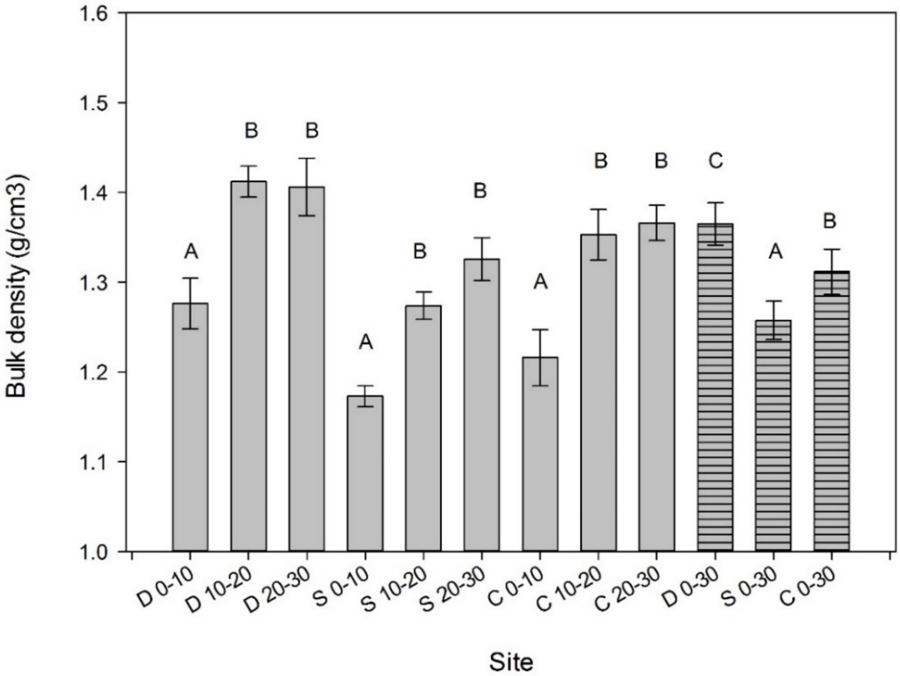


Figure 4.2 Bulk density (g/cm3) for individual depth increments of the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Letters indicate significant differences when individual depth increments (e.g. 0-10 cm) are compared across all sites (increments that do not share the same letter are significantly different). Error bars are 95% confidence interval.

Total porosity

Total porosity, also a primary indicator for soil natural capital, for the DF, SF and CS is presented in Figure 4.3. Total porosity is inversely related to bulk density (Error! Reference source not found.) and the results illustrate this relationship. There were significant differences ($P < 0.05$) as a result of site for total porosity integrated over the 0-30 cm depth. The DF had a significantly lower total porosity (48.5 ± 0.9%) than both SF (53 ± 1%) and CS (51 ± 1%) while total porosity at the CS was also significantly lower than at the SF. Total porosity was also significantly affected by depth. Total porosity declined significantly from the 0-10 cm increment to the 10-20 cm increment across all sites. For example on the DF there was a significant decrease in total porosity from the 0-10 cm increment (52 ± 1%) to the 10-20 cm increment (47 ± 1%). In contrast there were no significant differences for the site-depth interaction

4.3 Macro-porosity

Macroporosity, a more sensitive soil natural capital and quality indicator than total porosity, for the DF, SF and CS is presented in Figure 4.4**.** There were significant differences ($P < 0.05$) as a result of site for macroporosity integrated over the 0-30 cm depth. The DF had a significantly lower macroporosity (9 ± 1%) than both SF (19 ± 1%) and CS (15 ± 1%) while macroporosity at the CS was also significantly lower than at the SF. Macroporosity was also significantly affected by depth. Macroporosity increased significantly with depth for all sites except for 10-20 cm and 20-30 cm on the SF (20 ± 1% and 21 ± 1% respectively) and notably on the DF for 0-10 cm and 10-20 cm (9 ± 1% and 7 ± 1%). Finally the site-depth interaction had a significant effect on macroporosity and all of the depth increments on the DF had significantly lower porosities than the corresponding increments on the SF and CS. For example the 0-10 cm increment on the DF (9 ± 1%) was significantly lower than the same increment on the SF (17 ± 1%) and the CS (12 ± 1%). Likewise the increments on the CS were always significantly lower than the corresponding increments on the SF.

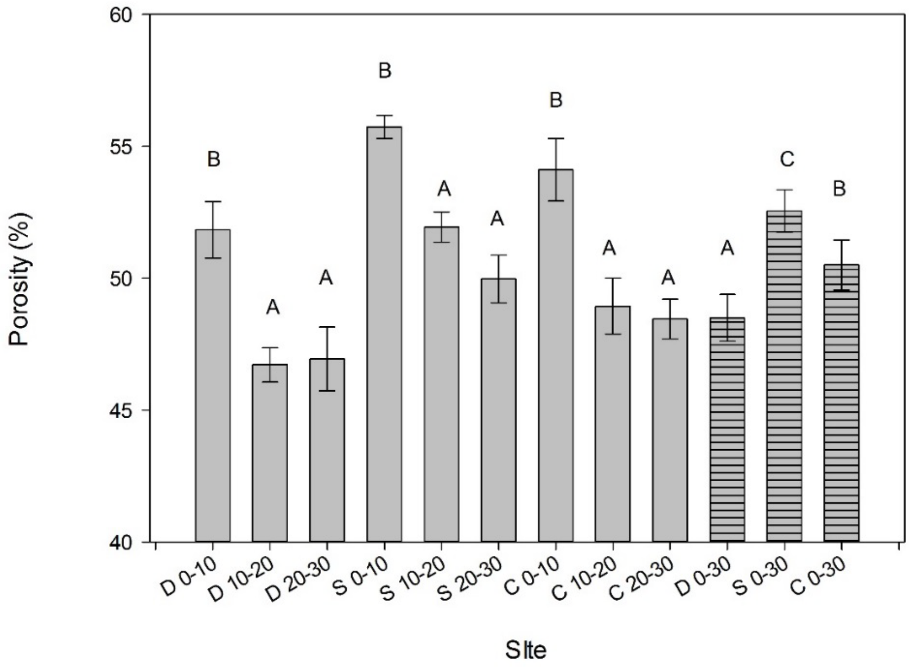


Figure 4.3 Total porosity (%) for individual depth increments of the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Letters indicate significant differences when individual depth increments (e.g. 0-10 cm) are compared across all sites (increments that do not share the same letter are significantly different). Error bars are 95% confidence interval.

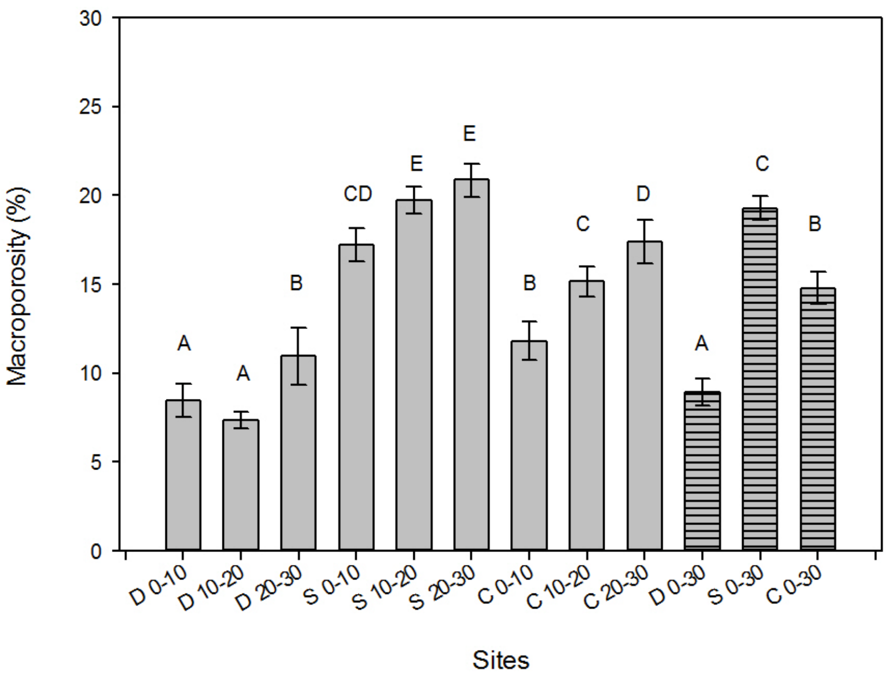


Figure 4.4 Macroporosity (%) for the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different ($p < 0.05$). Error bars are 95% confidence interval.

4.4 Total drainage porosity (0-10kPa)

Total drainage porosity, the readily drained pore space occupied by water between saturation and field capacity (-10 kPa tension), is presented in Figure 4.5. There were significant differences ($P < 0.05$) as a result of site for total drainage porosity integrated over the 0-30 cm depth. The DF had a significantly lower total drainage porosity (11 ± 1%) than both SF (21 ± 1%) and CS (17 ± 1%), while drainage porosity at the CS was also significantly lower than at the SF. Drainage porosity also increased significantly with depth from 0-10 cm to 10-20 cm for the SF (19 ± 1% to 22 ± 1%) and the CS (14 ± 1% to 18 ± 1%). However, following the same trend as for macroporosity, there was no significant increase on the DF from 0-10 cm to 10-20 cm (10 ± 1% to 9 ± 1%). Finally the site-depth interaction also had a significant effect on total drainage porosity and all of the depth increments on the DF had significantly lower porosities than the corresponding increments on the SF and CS. For example the 0-10 cm increment on the DF (10 ± 1%) was significantly lower than the 0-10 cm increment on the SF (19 ± 1%) and the CS (14 ± 1%). Likewise the increments on the CS were always significantly lower than the corresponding increments on the SF.

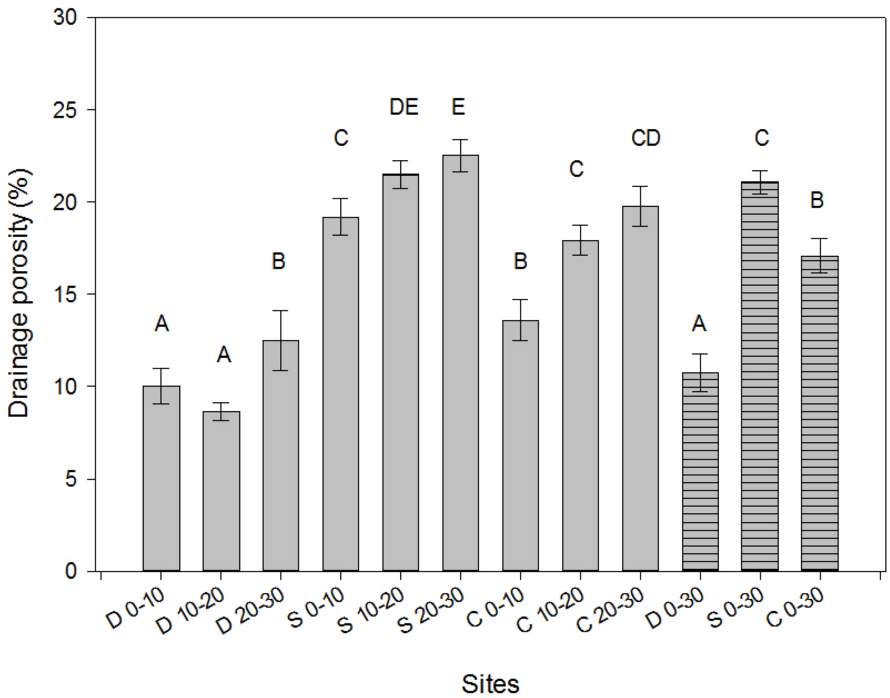


Figure 4.5 Total drainage porosity (%) of the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

4.5 Water content at -10 kPa (field capacity)

Water content at -10 kPa, the water content after rapid drainage has occurred, is presented in Figure 4.6. There were significant differences ($P < 0.05$) as a result of site for water content held at -10 kPa integrated over the 0-30 cm depth. The DF had a significantly higher water content at -10 kPa (38 ± 1%) than both the SF (32 ± 1%) and CS (33 ± 2%), which were not significantly different. Water content at -10 kPa also decreased significantly with depth for all sites. For instance on the DF water content decreased significantly from 0-10 cm (42 ± 1%) to 10-20 cm (38 ± 1%) to 20-30 cm (35 ± 2%). Finally the site-depth interaction also had a significant effect on water content at -10 kPa, and all of the depth increments on the DF had significantly higher water contents than the corresponding increments on the SF and CS with the exception of the 0-10 cm increment where water contents on the DF and CS were similar. For the 10-20 cm increment water content on the DF was 38 ± 1%, significantly higher than the SF (30 ± 1%) and the CS (31 ± 2%).

4.6 Water content at -40 kPa

Water content at -40 kPa, the point at which plant water extraction starts to become difficult and which is also used alongside water content at -100 kPa to calculate readily available water, is presented in Figure 4.7. Results at this matric potential showed very similar trends to at -10 kPa and there were significant differences ($P < 0.05$) as a result of site for water held at -40 kPa integrated over the 0-30 cm depth. The DF had a significantly higher water content at -40 kPa (35 ± 1%) than both the SF (28 ± 2%) and CS (30 ± 2%) which were not significantly different. Water content at -40 kPa also decreased significantly with depth for all sites except for from 10-20 cm to 20-30 cm on the CS. For instance on the DF water content decreased significantly from 0-10 cm (39 ± 1%) to 10-20 cm (36 ± 1%) to 20-30 cm (31 ± 1%). Finally the site-depth interaction also had a significant effect on water content at -40 kPa and all of the depth increments on the DF had significantly higher water contents than the corresponding increments on the SF and CS with the exception of the 0-10 cm increment where water contents on the DF and CS were similar. For the 10-20 cm increment water content on the DF was 36 ± 1%, significantly higher than the SF (27 ± 2%) and the CS (27 ± 1%).

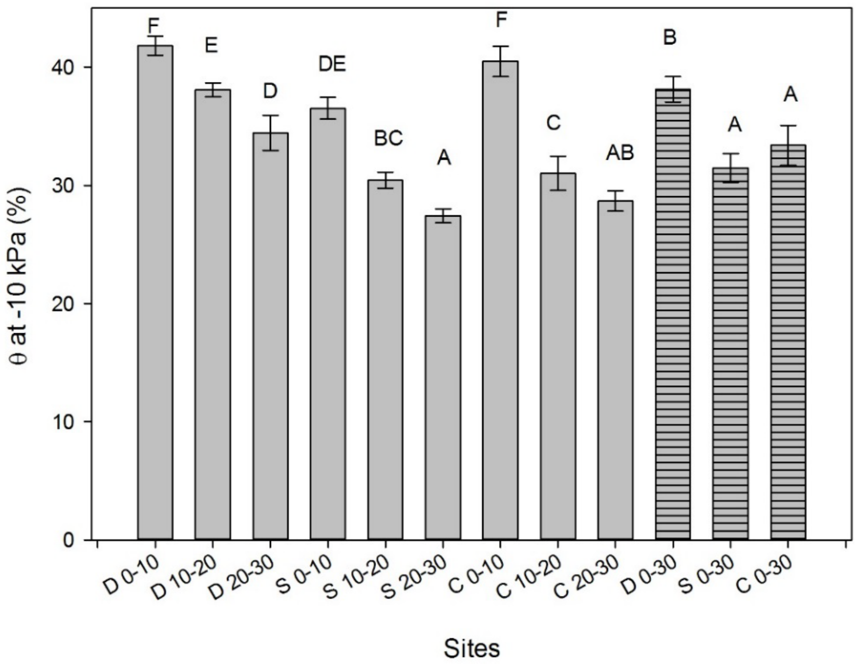


Figure 4.6 Water held at -10 kPa across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

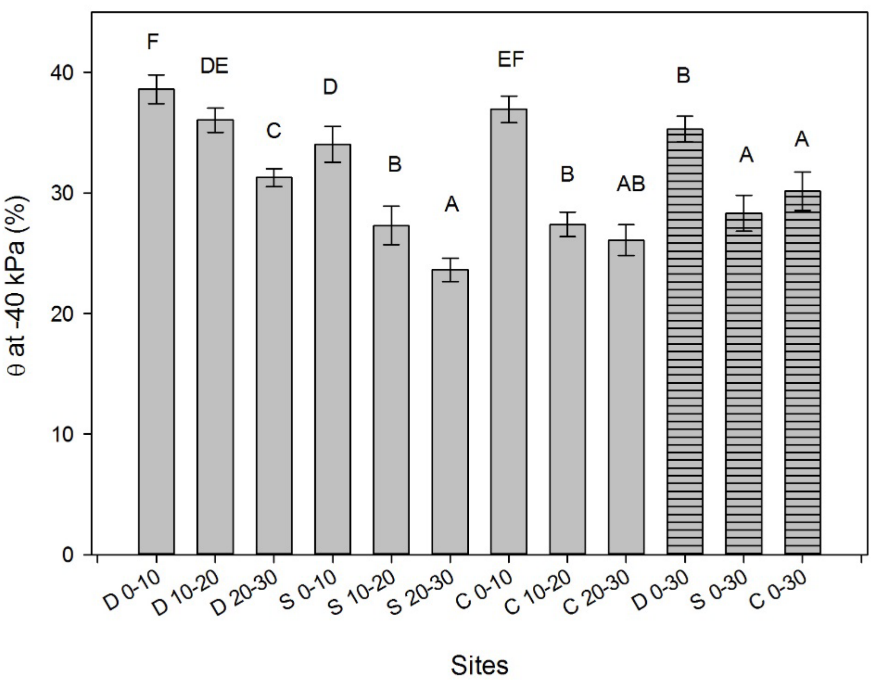


Figure 4.7 Water held at -40 kPa across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

4.7 Water content at -100 kPa

Water content at -100 kPa, also known as the trigger point for grasses below which production becomes limited, is presented in Figure 4.8. Results at this matric potential showed very similar trends to at -10 and -40 kPa and there were significant differences ($P < 0.05$) as a result of site for water held at -100 kPa integrated over the 0-30 cm depth. The DF had a significantly higher water content at -100 kPa (32 ± 1%) than both the SF (24 ± 1%) and CS (26 ± 1%), which were not significantly different. Water content at -100 kPa also decreased significantly with depth for all sites except from 0-10 cm to 10-20 cm on the DF and from 10-20 cm to 20-30 cm on the CS. For instance on the DF the change in water content was not significant from 0-10 cm (35 ± 1%) to 10-20 cm (33 ± 1%) but there was a signficiant decrease to 20-30 cm (27 ± 1%). Finally the site-depth interaction also had a significant effect on water content at -100 kPa and all of the depth increments on the DF had significantly higher water contents than the corresponding increments on the SF and CS with the exception of the 0-10 cm increment where water contents on the DF and CS were similar. For the 10-20 cm increment water content on the DF was 36 ± 1%, significantly higher than the SF (27 ± 2%) and the CS (27 ± 1%).

4.8 Readily available water storage

4.8.1 -10 to -40 kPa

Water held between -10 to -40 kPa, one measure of plant readily available water, is presented in Figure 4.9. The water extracted between -10 kPa and -40 kPa is calculated as a difference between water contents at these two matric potentials. The strong tendency for the water contents at all sites to follow the same trends (DF > CS = SF) meant that the differences were very similar. There were no significant differences between treatments as a result of site, depth or, as a result, site-depth interaction. For example water held between -10 to -40 kPa ranged from 2.8 ± 0.7% at the DF to 3 ± 1 % at the SF to 3 ± 1% at the CS. Results from θ at -10 kPa and -40 kPa, above, both show the same trends which indicates that there would be no difference when subtracted the two are subtracted. Furthermore the large uncertainties are the result of subtraction which leads to differences between treatments becoming difficult to detect statistically.

4.8.2 -10 to -100 kPa

Water held between -10 to -100 kPa, another measure of plant readily available water, is presented in Figure 4.10. Again there were no significant differences between treatments as a result of site, depth or, as a result, site-depth interaction. For example water held between -10 to -100 kPa ranged from 7 ± 1% at the DF to 8 ± 1% at the SF to 8 ± 1% at the CS. The lack of significant differences arises for the same reason as for readily available water (-10 kPa to -40 kPa): the differences in water contents between -10 kPa and -100 kPa are similar because the water contents at these two matric potentials follow the same trends across the sites. Furthermore, the large uncertainties that the result from the subtraction leads to differences between treatments becoming difficult to detect statistically.

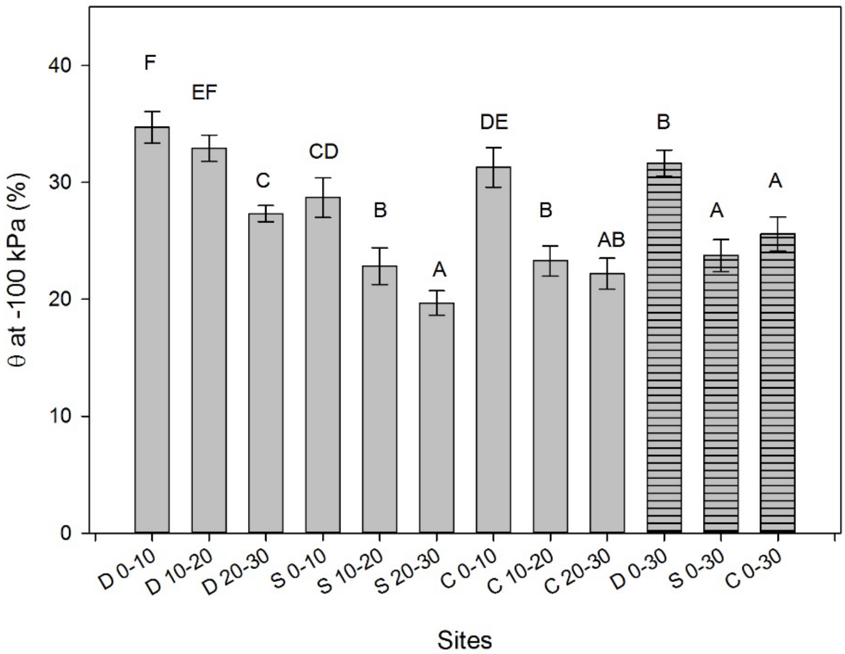


Figure 4.8 Water held at -100 kPa across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

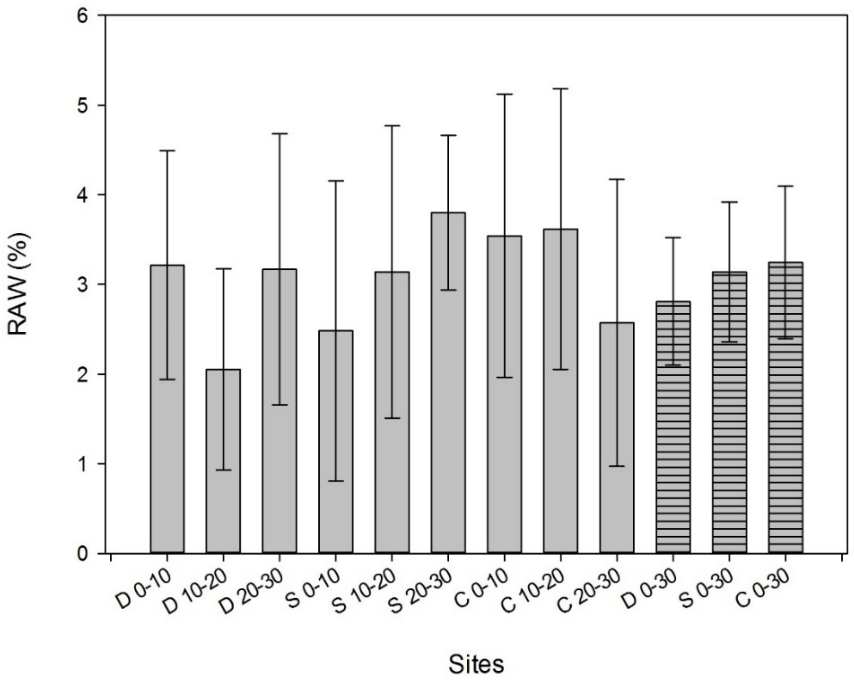


Figure 4.9 Readily available water storage (-10 to -40 kPa) of the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. There were no significant differences. Error bars are 95% confidence interval.

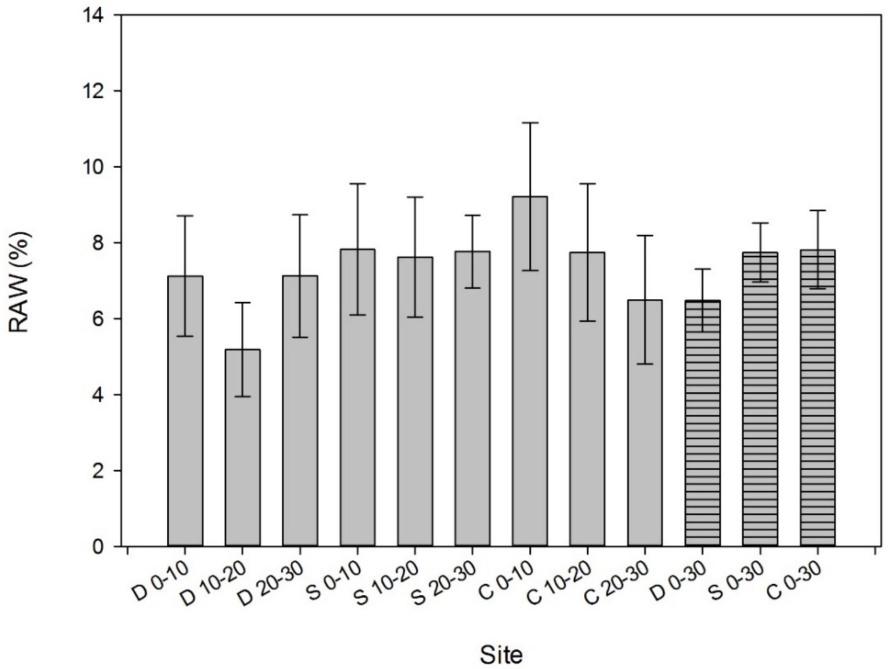


Figure 4.10 Readily available water storage (-10 to -100 kPa) of the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. There were no significant differences. Error bars are 95% confidence interval.

4.9 Carbon concentration

Organic carbon concentration, a primary variable determining the C storage in soils, is presented in Figure 4.11. There were no significant differences as a result of site for C concentration integrated over the 0-30 cm depth. However C concentration did decrease significantly ($P < 0.05$) with depth for all sites. For instance, on the DF C concentration decreased significantly from 0-10 cm (3.2 ± 0.1%) to 10-20 cm (2.3 ± 0.1%) to 20-30 cm (1.4 ± 0.2%). There were also no significant differences as a result of site-depth interaction between any of the treatments.

4.10 Carbon density

Carbon density, a product of organic C concentration and bulk density, is a measure of the volumetric concentration of organic C content of a soil (Figure 4.12)**.** There were no significant differences as a result of site for C density integrated over the 0-30 cm depth. However, C density did decrease significantly ($P < 0.05$) with depth for all sites. For instance on the DF, C density decreased significantly from 0-10 cm (40 ± 1 kg C/m^3) to 10-20 cm (32 ± 2 kg C/m^3) to 20-30 cm (20 ± 3 kg C/m^3). There were also no significant differences as a result of site-depth interaction between any of the treatments.

4.11 Carbon equivalent mass method

The soil organic C equivalent-mass, quantifies C stored within a given soil depth increment on an area basis (kg C m^{-2}) (Figure 4.13). C mass (referred to as storage) decreased significantly ($P < 0.05$) with depth for all sites. For instance on the DF, C storage decreased significantly from 0-10 cm (4.0 ± 0.1 kg C/m^2) to 10-20 cm (3.2 ± 0.1 kg C/m^2) to 20-30 cm (2.0 ± 0.3 kg C/m^2). There were no significant differences as a result of site-depth interaction between any of the treatments. Furthermore, when results for C storage were integrated over the 0-30 cm depth there were no significant differences between sites.

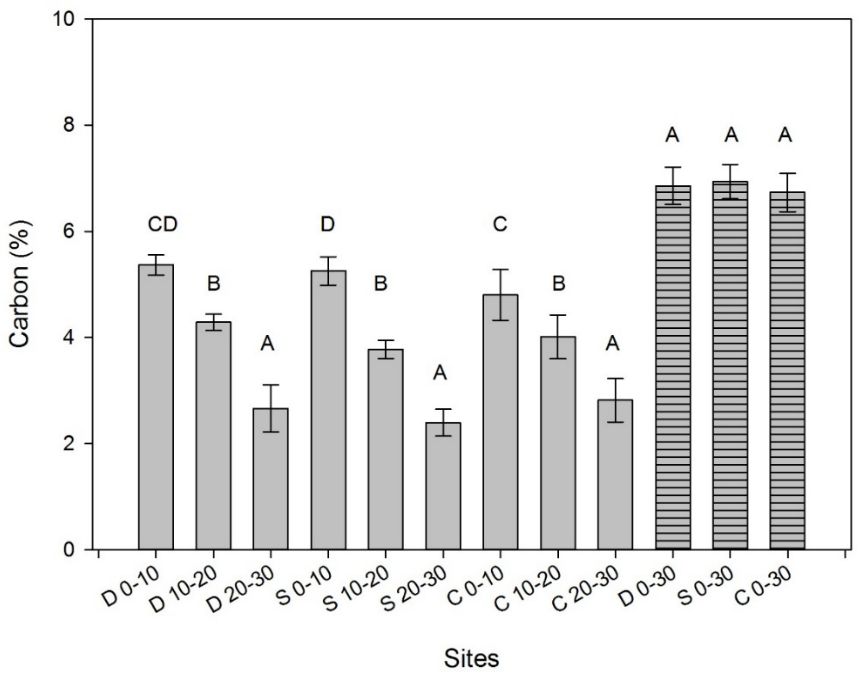


Figure 4.11 Carbon concentration (%); across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site whereas horizontal lined bars show integrated 0-30 cm depths. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

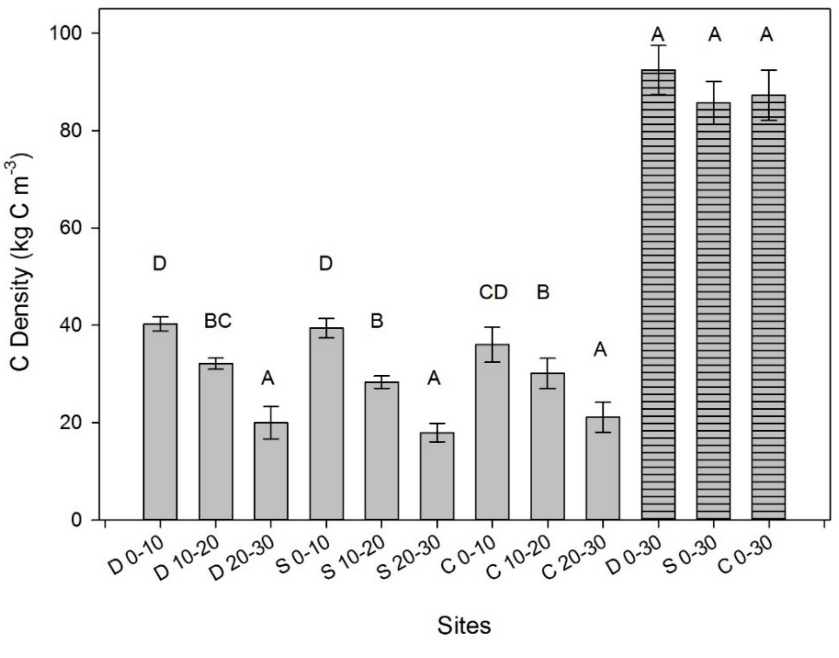


Figure 4.12 Carbon density (kg C m^{-3}) across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

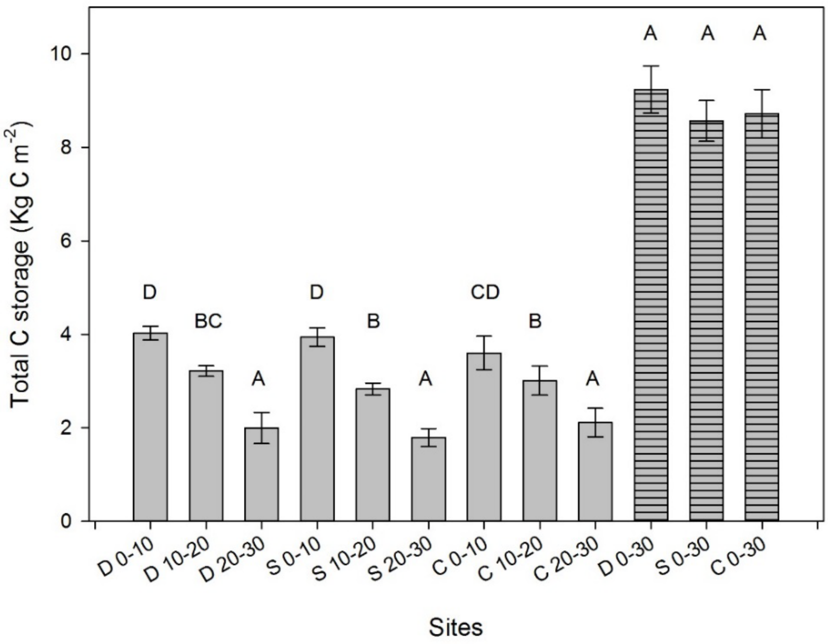


Figure 4.13 Total C storage (kg C m^{-2}) across the three sites (D –dairy farm, S – sheep farm, C – control site). Grey bars show 10 cm depth increments for each site and horizontal lined bars show integrated 0-30 cm increments. Increments that do not share the same letter are significantly different (p< 0.05). Error bars are 95% confidence interval.

Chapter 5

Discussion

This study aimed to determine the impact of intensifying land use practices on the physical natural capital of a Templeton silt loam soil, evaluating the effect on soil physical indicators measured at 10 cm increments to a total depth of 30 cm. This depth was chosen based on findings from West (2012) which detailed a study of SOC content carried out on the same soil type and where no significant changes in SOC where found below a depth of 30 cm. Further support for sampling to this depth is that the international standard for carbon accounting and forestry monitoring is 0–30 cm (Lambie, 2013) . In comparison, one of the weaknesses of the national soil quality monitoring programme is that soil samples are taken to a depth of only 10 cm when studies have reported on effects of grazing on soil physical properties to a depth of 20 cm (Drewry*, et al.*, 2008). The 0-30 cm depth is also where the bulk of the pasture root mass is located, and so is crucial for water and nutrient extraction (Evans, 1978).

5.1 Macro and drainage porosity

Macroporosity (pores > 30 ųm) for the DF did not change from 0-10 cm to 10-20 cm (9 ± 1% and 7 ± 1% respectively) but increased for the 20-30 cm increment (10 ± 2%). This indicates that, although compaction of macropores is occurring across all increments, compaction for the 0-20 cm increment is greater than that below the top 20 cm of the soil profile. These results agree with those of Houlbrooke & Laurenson (2013) who found that changes in macroporosity due to compaction were not evident below a depth of 20 cm. It has been suggested by Lambie (2013) that soil samples for the national soil quality monitoring programme be increased from a depth of 10 cm to a depth of 20 cm or 30 cm for a more holistic picture on the state of soil physical properties.

Macroporosity was significantly lower for the DF (9 ± 1%) than both the SF (19 ± 1%) and the CS (15 ± 1%). This suggests that intensification is having a significant effect on the DF. In particular the 0-10 cm and 10-20 cm increments on the DF are important because both have values for macroporosity < 10%. Sparling & Schipper (2002) argue that macroporosity values of > 10% are needed to maintain pasture production near optimum. In addition they define target ranges for macroporosity as part of the national soil quality indicator programme (Table 5.1). For soils under pasture macroporosity values < 8% are considered low and could restrict pasture growth; Macroporosity for the DF 10-20 cm increment was 7 ± 1%, a level where less than optimum production could be expected.

Table 5.1 Target values for macroporosity for pasture, cropping & horticulture and forestry (Sparling, et al., 2008).

Pasture, cropping & horticulture	0	**6**	8	**30**	40
Forestry	0	**8**	10	**30**	40
	Very low	Low	Adequate	High	

Macroporosity and bulk density are the two soil physical natural capital indicators that are primarily used to identify compaction. The effect of irrigation alone on soil physical properties has been previously found to improve soil structure, increasing soil aggregate stability and macroporosity (Blanco-Canqui, *et al.*, 2010; Singh, *et al.*, 2013). The addition of grazing to both irrigated and dryland pastures is found to decrease macroporosity, while the intensity of compaction from grazing has been found to increase in relation to moisture (Drewry, *et al.*, 2008; Houlbrooke & Laurenson, 2013). Therefore, it is expected that low values of macroporosity for the 0-10 cm and 10-20 cm increments on the DF is a result of compaction from grazing. Significantly higher macroporosities on the dryland SF for the 0-10 cm increment (17 ± 1%) are double that on the irrigated DF for 0-10 cm (9 ± 1%), indicating that the increased grazing pressure alongside higher soil moisture content under irrigation are reducing soil macroporosity. In agreement, Houlbrooke & Laurenson (2013) found similar values for, and changes of macroporosity with stocking intensity. On the dryland sheep farm for the 0-10 cm increment macroporosity was 18 ± 4% (± LSD, $P < 0.01$), significantly higher than the value for the irrigated DF (10 ± 4%).

While values of macroporosity were significantly lower overall for the DF than for the SF and the CS, the SF had a higher macroporosity for the 0-10 cm, 10-20 cm and 20-30 cm increments than the CS. The CS was subject to greater vehicle traffic than the SF, because the site is regularly mowed, however sampling locations at the site were chosen to avoid locations where other vehicles travel. Comparison of soil particle sizes between sites (Figure 4.1) showed that distributions were essentially similar, although the fine sand (0.2-0.06 mm) content on the CS at 25 ± 2%, was lower than the SF at 29 ± 2%. However, this small difference is not expected to be the driver behind the differences in macroporosity. Similarly there was no significant difference in carbon density or storage between the sites that could explain the difference. Results of soil fertility tests showed that fertility at the SF was higher than on the CS (base saturation % and olsen P values), potentially as a result of some historic fertiliser application and the return of manure to the site during grazing. However, although fertility did vary between the sites, all values were within the adequate range for soil physical quality that Sparling, *et al.* (2008) have defined for pasture land use. In addition, higher earthworm numbers were noted on the SF during sampling than on the CS. The activity of earthworms has been shown to increase soil macroporosity (Francis & Fraser, 1998). Increased fertility and earthworm numbers at the SF in comparison to the CS are possibly responsible for the higher macroporosity at the site.

Bulk density values were found to be significantly higher on the DF (1.40 ± 0.02 g cm^{-3}) than both the SF (1.26 gcm^{-3} ± 0.02) and the CS (1.31 ± 0.02 g cm^{-3}), indicating increased compaction on the DF in agreement with macroporosity values. There was also an increase in bulk density from the 0-10 cm increment to the lower increments on all sites. Bulk density values show the inverse relationship to values of total porosity (Figure 4.3). Bulk density is not as sensitive an indicator of compaction as macroporosity (Lambie, 2013) and this can be seen by the large target range 0.7–1.4 gcm^{-3} that has been identified for Pallic soils (Sparling*, et al.*, 2008), the subject of this study. This is because of the effect of SOC on bulk density which can reduce the changes seen between depths. SOC tends to reduce bulk density because it has a lower density than soil and because it improves the soil structure by assisting with aggregate development and providing a surface for structurally important base cations (McLaren & Cameron, 1996). This interaction can be seen on the DF at the 10-20 cm increment, which has the same bulk density as the 20-30 cm increment (1.41 ± 0.02 g cm^{-3} versus 1.41 ± 0.03 g cm^{-3}) despite having significantly higher SOC by both density and mass than the 20-30 cm increment. This indicates that the effect of compaction is extending down to this horizon, but this conclusion is not as obvious from bulk density data as it is from macroporosity data. Bulk density is maintained as a soil physical quality indicator because, as well as particle density, it is a necessary factor in the calculation of macroporosity and for the conversion of gravimetric parameters to volumetric (Lambie, 2013).

Figure 5.1 provides an analysis of macroporosity results (black bars) alongside drainage porosity (white) and total porosity (grey). The same pattern of results were present for drainage porosity as macroporosity. The difference between macroporosity and drainage porosity (-5 kPa to -10 kPa), represented by the difference in the heigh of the black and white bars in Figure 5.1**,** is called mesoporosity. Mesoporosity remains relatively constant across all depths and sites, which indicates that differences in total porosity, with values for the 0-30 cm increments significantly lower on the DF than on the CS and, respectively, on the SF (Figure 4.3), correspond to a reduction in macroporosity due to macropore collapse resulting from compaction. Houlbroooke & Laurenson (2013) also found a decrease in macroporosity and an increase in microporosity with increasing intensification from dryland to irrigated cattle treatments. Despite this increase in microporosity, Houlbroooke & Laurenson (2013) found that there was no increase in drainage porosity, but there was an increase in the amount of water held at PWP on the irrigated cattle treatments. This finding will be discussed in relation to results from this study in the following section.

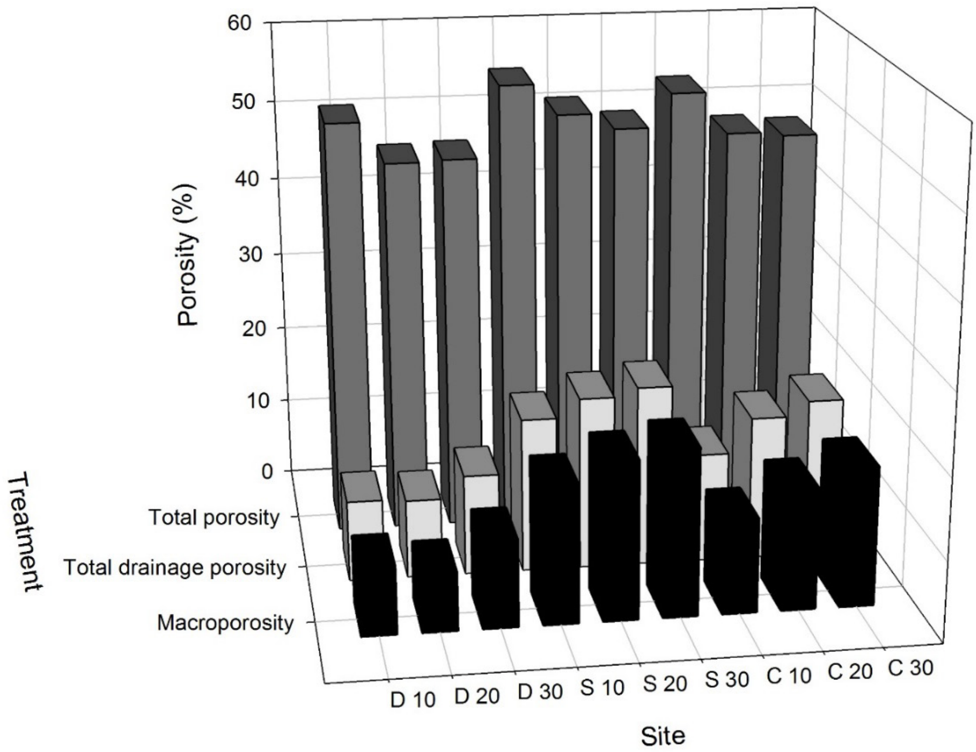


Figure 5.1 Comparison of total porosity, total drainage porosity (0 to -10kPa) and macroporosity (0 to -5 kPa) across sites and depth increments. Annotations site – depth combinations, e.g. D 10 (Dairy 0-10 cm), S 20 (Sheep 10-20 cm), C 30 (Control 20-30 cm).

The SINDI soil quality calculator was developed by Landcare Research using findings from the 500 Soils Project and assisted by studies such as that of Sparling, et al. (2008). It compares soil results for seven indicators, including the physical indicators bulk density and macroporosity, against target values, such as those presented in Table 2.1 and Table 5.1, to determine if soils are within optimum ranges or not. The tool takes into account soil type and land use when determining soil quality. Using the SINDI tool to analyse findings for the DF, SF and CS across the 0-30 cm increment, the bulk densities for the DF were rated as between compact and very compact, and macroporosity as low. In comparison, the SF rated as adequate for both bulk density and macroporosity, and the CS rated as average and low respectively (Landcare Research, 2014a).

Dominati, *et al.* (2010) developed a framework to assess soil natural capital where soil properties are assessed alongside processes that can have an impact on them (such as compaction). Properties are assessed together with the drivers of the processes (land use practices causing compaction), and the ecosystem services that the soil provides (provision of food) and the human needs that this ecosystem service fulfils (physiological needs). Assessing soil physical properties on the DF, SF and CS in terms of the soil natural capital framework shows that there has been a decrease in natural physical capital on the DF. In terms of soil physical quality the low macroporosity on the CS is seen as undesirable, although when this result is assessed using the natural capital framework it is obvious that it is unimportant because it is unlikely to affect the soils ability to provide its intended ecosystem services at this site, that of aesthetics for mowed lawn. Contrastingly, in terms of soil physical natural capital, the decrease in macroporosity on the DF is likely to be affecting the soil's capacity for optimum provision of ecosystem services (to grow maximum pasture) and consequently its optimum capacity to fulfil human needs into the future (food production). Use of soil quality indicators showed that three of the five tested soil fertility- related properties (Olsen P, pH and total C) were within the accepted average range. However, this form of assessment does not place appropriate emphasis on the importance of the two indicators, macroporosity and bulk density, that were affected. Use of the natural capital framework allows for evaluation of not just the current state of the soil, but its continued change, and the importance and effect of the soil quality measurement in the wider ecosystem services that soils provide.

5.2 Water storage porosity

Water storage, the amount of water held between -10 to -40 kPa and -10 to -100 kPa, did not show any significant differences between any of the treatments for either matric potential range (Figure 4.9 and Figure 4.10). This result in itself is interesting as it shows that intensifying land use practices did not have a measureable impact on the RAW of the soil. In comparison other studies have found that there is a significant decrease in RAW with irrigation and increased compaction (Houlbrooke & Laurenson, 2013). The reason for these contrasting findings is because while Houlbrooke & Laurenson (2013) observed a decrease in macroporosity with irrigation, and increased compaction, the majority of the changes affected pores ≤ 3 µm in diameter, those holding water at matric potentials of ≤ -100 kPa. Changes between the DF, SF and CS were the result of a compaction driven decrease in the number of macropores and these influenced water held at all other pressures measured. Because there was no change in the numbers of these pores, holding water between -10, -40 and -100 kPa.

This result is similar to a study by Cossens & Rickard (1966) on the effects of irrigation on Pallic soils where no significant changes were observed in AWC between dryland (71 mm AWC) and irrigated (75 mm AWC) soils in central Otago. The same study found that the AWC of Semi-arid soils increased with irrigation while the Pallic soils were unchanged. The increase in the AWC of the Semi-arid soils was thought to be a result of an increase in SOC for the irrigated soils. This result will be discussed in the following section in relation to SOC results in our study. Subsequent trials testing the effect of irrigation on Semi-arid, Pallic and Brown soils across the wider central Otago area found that the AWC of Pallic soils did increase and it was the Brown soils instead that showed no change (Cossens & Rickard, 1969; Rickard & Cossens, 1968).

The differences in water content (θ) between sites at -5 kPa, the result of the negative effects of compaction on macroporosity, have influenced the differences in θ seen between sites at pressures of -10, -40 and -100 kPa. For example, the effects of compaction on the DF meant a decrease in macroporosity and an increase in the amount of water held at -5 kPa. From the results it is apparent that there were no significant changes to pores between 300 μm and 3 μm in diameter (meso and micro pores holding water between -5 kPa and -100 kPa) as a result of irrigation and grazing. However, there is a difference in the micro-pore volume holding water at pressures lower than -100 kPa on the DF. The DF has the highest water content at -100 kPa (32 ± 1%) in comparison to the SF (24 ± 1%) and the CS (26 ± 1%). This indicates an increase in micropores smaller than 3 μm in diameter holding water at pressures lower than -100 kPa. From results of θ at -100 kPa, shown in Figure 4.8, it is apparent that there has been a significant increase ($p < 0.05$) in micropores < 3 μm across all depths on the DF, in comparison to the SF and CS, with greatest increases for the 0-10 cm increment. It is not known whether the change in pore sizes is a result of compression of macropores straight to micropores < 3 μm or if there is a decrease in the size of all pores across the range. However, despite the process, the result is again supported by similar findings from Houlbrooke & Laurenson (2013) who determined that cattle irrigated treatments had significantly greater values for θ at PWP than dryland cattle and sheep grazed treatments. As a result there was a decrease in AWC for the cattle irrigated treatments as more water was held in residual micropores (< 0.2 μm in diameter) and therefore unavailable to plants.

In this study the DF, SF and CS vegetation cover was pasture, a mixed ryegrass white clover sward at the DF and SF and a range of mixed pasture species at the CS. McLaren & Cameron (1996) define the the critical soil matric potentials (trigger point) for extraction by grasses as ranging from -30 to -100 kPa. The trigger point is defined as the matric potential below which plants can no longer extract enough water for maximum growth. In order to maintain maximum crop yields irrigation should be applied when these matric potentials are reached, -30 kPa is used when evapotranspiration is high and water needs to be applied more regularly. For this reason measurements of θ were not taken at pressures greater than -100 kPa such as PWP.

Because there were no changes in RAW, from -10 to -40 kPa or -10 to -100 kPa, between the DF, SF or CS there is no change to the amount of water readily available to plants. Although there is evidence that the number of pores < 3 μm in diameter (where water is held at matric potentials of less than -100 kPa) increase on the DF this is not expected to affect irrigation practices on the farm because in order to maintain maximum crop yield, soil moisture for growing pasture should be targeted to be maintained by irrigation at matric potentials between -10 and -100 kPa. Although findings of RAW indicate that it is not necessary to change irrigation practices the reduction in macroporosity on the DF is expected to lower the infiltration rate meaning that surface runoff could be triggered more frequently (Houlbrooke & Laurenson, 2013).

In addition when compaction occurs in the presence of animal excreta such as urine or dung, these changes in the soil physical characteristics potentially lead to the formation of local hot spots for N_2O fluxes from soil. Under moist soil conditions, such as those resulting from irrigation, compaction has been shown to increase fluxes of urine-derived N_2O from 0.9% to 4.9% owing to increased denitrification under increasing anaerobic conditions (van Groenigen*, et al.*, 2005). In agreement Balaine (2012) found that, in the presence of urea N, increasing bulk density due to compaction, resulted in an increase in N_2O fluxes while at higher matric potentials N_2O can be further reduced to N_2. Results showed that higher N_2O fluxes, as the result of urea application, occurred at -6 kPa at a bulk density of ≤ 1.3 gcm^{-3}. Interpretation of these results in relation to findings on the DF indicate that there is the potential that DF N_2O fluxes could increase as a result of a decrease in macroporosity and increase in bulk density.

5.3 Carbon

It is proposed that the lack of significant changes in SOC content between the DF, SF and CS (Figure 4.11) for any depth increment is reasonable and supported by literature. The study by West (2012), comparing SOC on the LUDF with a control site, found that there was no significant difference in SOC content between the two sites in the 0-30 cm depth. There was a change in SOC content from 30-40 cm, but this was reasoned to be a result of a marked difference in soil particle size between sites at this depth. Although West (2012) did not analyse the statistical significance of the change in SOC content with depth, results do trend downwards with depth, in agreement with the findings of this study for the DF, SF and CS, where SOC content decreases significantly with depth at all sites.

Results for C density (Figure 4.12) and C storage (Figure 4.13) for the DF, SF and CS were similar to those for C content (Figure 4.11) as there were no significant differences between sites. The 0-30 cm increment values for C storage at the DF, SF and CS (9.2 ± 0.3 kg C/m^2; 8.6 ± 0.2 kg C/m^2 and 8.7 ± 0.3 kg C/m^2 respectively) (n=45 for each site) were similar to those measured by West (2012) for C storage on the LUDF (10 ± 2 kg C/m^2) (n=18) and control site (8 ± 2 kg C/m^2) (n=6). The results of West (2012) use the standard deviation as the confidence interval in comparison to our study where 95% confidence intervals were used. In both this study and West's (2012) the C storage values decreased significantly with depth at all sites, when using the equivalent mass method to calculate C storage for each depth increment. However, in this study there was no significant difference between the DF, SF and CS when comparing the same depth increments. There were significant differences between increments, for example between 0-10 cm and 10-20 cm. In comparison, West

(2012) found there was no significant change in C storage between the LUDF and the control site to 10 cm, but at the 15 cm, 20 cm and 30 cm depths the DF had significantly higher C storage than the control site.

West (2012) also reported on previous studies carried out on the LUDF (J. Moir, personal communication, October 2 2012), one prior to conversion in 2001 and one in 2011. C storage was measured for the uppermost 7.5 cm in these studies. In 2001 C storage was 2.2 kg C/m^2 and for 2011, 3.5 kg C/m^2. However no values for uncertainty are indicated for these studies. In order to compare values of C storage for the DF and LUDF (West, 2012) with the findings of these earlier studies, calculations were carried out for the 0 - 7.5 cm depth. For the top 7.5 cm the DF had 3.0 kg C/m^2 and the LUDF had 3.5 kg C/m^2. These results show that the 2011 measurements at the LUDF are similar to those of West (2012) which are in turn reasonably similar to those obtained in our study at the DF. The slightly lower values obtained at the LUDF in our study could be as a result of sampling at a different paddock to the previous studies with variations in soil types as a result.

Literature suggests an increase in SOC content with irrigation (Rickard & Cossens, 1968; Singh*, et al.*, 2013; Trost*, et al.*, 2013). However, these studies tend to be carried out under Arid or Semi-arid conditions with low natural fertility where the addition of irrigation increases plant growth and, therefore, organic matter returns to the soil. Trost, *et al.* (2013) report that there is an increase in SOC for soils found in Arid and Semi-arid regions but less of an increase in SOC for soils with higher initial SOC, found in higher rainfall environments. They suggest that higher microbial levels, in soils with a high initial SOC, quickly decompose any additional OM inputs to the system as a result of increased plant growth under irrigation. Therefore no significant increase in SOC is seen in these soils. We hypothesise that a reason for the lack of difference in SOC between the DF, SF and CS is the higher fertility on the DF and its history of irrigation. High microbial populations on the DF, sustained by the moist, fertile conditions, mean that a stable level of SOC has been reached where inputs of OM are balanced with decomposition by microbes, maintaining a SOC similar to that measured at the SF and CS.

In terms of changes in SOC with depth, the measurements of C content, C density and C storage showed significant decreases with depth from 0-10 cm, 10-20 cm and 20-30 cm for all sites. Although West (2012) did not analyse the statistical significance of the change in C content or storage with depth results do trend downwards with depth in agreement with findings for the DF, SF and CS. These results are expected; highest levels of SOC are on the surface where the majority of OM additions from plants are deposited and SOC decreases with depth from the surface where OM additions are also less.

Use of SOC measurements for determining soil quality for the 0-10 cm increment show that SOC is within the normal range for all three sites (Landcare Research, 2014a). In comparison, when using the natural capital framework to assess the state of SOC at the sites the change in SOC overtime on the DF becomes an important consideration. If SOC on the DF was decreasing over time then this would mean that soil natural physical capital was declining as regulating ecosystem services such as carbon storage and regulation of N_2O and CH_4 would be negatively affected and therefore also human physiological needs (Dominati*, et al.*, 2010). However, if SOC levels were stable, as possibly suggested by the DF, SF, CS comparison in this study, then this would mean that the natural capital of the soil is unlikely to be changed as a result of SOC and it is changes in macroporosity that will have the most significant effects on optimising ecosystem services.

In conclusion macroporosity appears to be the property affected most significantly by changes in land use intensity. Irrigation and grazing together decreased macroporosity in the top 30 cm of the soil profile. As a result it is likely, on the DF, that the timing of grazing on moist soils and the timing of irrigation will be a key challenge for management. The risk of compaction is likely to be greatest when it coincides with irrigation or rainfall. Irrigation could be managed in accordance with this finding, reducing θ prior and during grazing when compaction risk of the soil is greatest.

5.4 Future research

Initial research focused on determining the effect of both irrigation and grazing on soil physical properties and it appears that there are negative effects on key physical properties as a result of both irrigation and grazing combined. This study highlighted the importance of the soil natural capital framework in analysing the effect of increasingly intensive land use practices on physical properties.

The soil natural capital framework appears to be a more holistic measure of the state of the soil than soil quality. It is suggested that case studies be carried out, where the natural capital framework is used to evaluate the current state of soil resources and to predict how these resources may change with time. These case studies would depict the steps required to use the framework to evaluate soils and would assist other land users in carrying out evaluations themselves. More specifically, the inclusion of a soil natural capital evaluation into the Farm Environment Management Plan (FEMP) templates would improve land user's understanding of the long term results of changes in the state of their soil.

Specifically to this trial, it is recommended that further research be carried out on the LUDF around mitigating the effects of compaction on soil macroporosity. The findings of this study have indicated that macroporosity is the physical property primarily affected by irrigation and grazing however further work is needed to determine what can be done from a management aspect to reduce compaction and maintain soil natural capital in the long term. To this end recommendations for further research include: establishing the critical moisture content for the soil, when maximum compaction can occur and it is beneficial to avoid grazing. Also establishing the optimal values for macroporosity on the farm, this could be done by comparing pasture growth under a non-treaded area of paddock with pasture growth under grazing, and researching the ability of macroporosity to recover if cultivation and pasture renewal is carried out.

Finally in relation to SOC it is suggested that the C storage on the LUDF is re-measured in a further 5-10 years. This would enable a conclusion to be reached in regard to whether a stable state of C storage has been reached.

Chapter 6

Conclusions

In this study soil physical properties were sampled to a depth of 30 cm to determine the effect of irrigation and grazing. Macroporosity was found to be the physical property that was primarily affected and that influenced the changes seen in other properties. Values for the 0-10 cm and 10-20 cm increments on the DF, where compaction of the irrigated soils resulted in the greatest reduction to macropores, were significantly lower ($p < 0.05$) than the 20-30 cm increment on the DF and the corresponding increments on the SF and CS. Macroporosity on the CS was also lower for all increments than the corresponding increments on the SF and it was suggested that this was owing to higher fertility and higher numbers of earthworms at the SF which increased macroporosity.

When compared to other studies these conclusions appear to be justified and it has been found elsewhere that irrigated cattle treatments have lower macroporosities than dryland cattle and sheep treatments. The same studies have also found that micropores ≤ 3 µm in diameter, holding water at -100 kPa to -1500 kPa, are negatively affected, porosity is reduced in relation to total porosity, by irrigation and grazing. While RAW, between -10 kPa and -100 kPa, was unaffected, the AWC, between -10 kPa and -1500 kPa, was reduced because of a reduction in the number of pores ≤ 3 µm in diameter. Similar results were obtained for the DF in this study while micropores on the SF and CS appeared unaffected. In our study RAW on the DF was indistinguishable from that at the SF and CS sites, however, there was an increase in the amount of water held at -100 kPa when compared with the other sites. As measurements were not taken at matric potentials less than -100 kPa it was not possible to tell how micropores < 3 µm in diameter were affected. From these findings it is suggested that the timing of grazing on moist soils will be a key challenge for management and soil physical properties would benefit from reduced grazing after significant rainfall events.

Bulk density was also found to be affected by irrigation and treading although it was not as sensitive to the changes in land management as macroporosity. Bulk density for each depth increment, 0-10 cm, 10-20 cm and 20-30 cm, changed depending on the amount of SOC in that horizon, however when results for 0-30 cm depth were compared bulk density on the DF was significantly higher than on the SF and CS. This was found to reflect the decrease in macroporosity on the DF in comparison to the other sites. These findings from our study, in agreement with other literature, indicate that while bulk density is an important physical property macroporosity is a more sensitive indicator for evaluating the effect of compaction.

Results for SOC were evaluated as C content, C density and C storage and no significant differences ($P > 0.05$) were found between the DF, SF and CS at any depth for any of these methods. A study carried out on the LUDF in 2012 found that the dairy farm had significantly higher SOC than a control site to depths of 15 cm, 20 cm and 30 cm. However these results were not very different from those obtained in our study and can be attributed to differences in the paddocks sampled. Further research is required in the future to determine if the SOC on the LUDF is remaining relatively constant.

Macroporosity is an indicator for evaluating soil quality and the soil physical natural capital. In our study evaluating the soil quality by comparing the results for physical indicators with established target ranges showed that determining the quality of the soil only gave an indication of the current state of the soil. It did not take into consideration the changes over time or the significance of different attributes in terms of providing ecological services and fulfilling human needs. In comparison, assessing the physical indicators in relation to the soil natural capital framework revealed that the soils were changing over time and properties, such as macroporosity, were being negatively affected. The natural capital framework revealed that these changes in properties over time could have a detrimental impact on the ecosystem services, such as food provision, and, in turn, human physiological needs.

In conclusion the soil natural capital framework provides a better approach for assessing the state of a soil than soil quality because the natural capital framework provides links to the socio-environmental impacts of the state and trends of the soil. Further research and case studies making use of the soil natural capital framework are suggested to improve land user’s understanding of this method of evaluating the state of the soil resource.

Appendix A

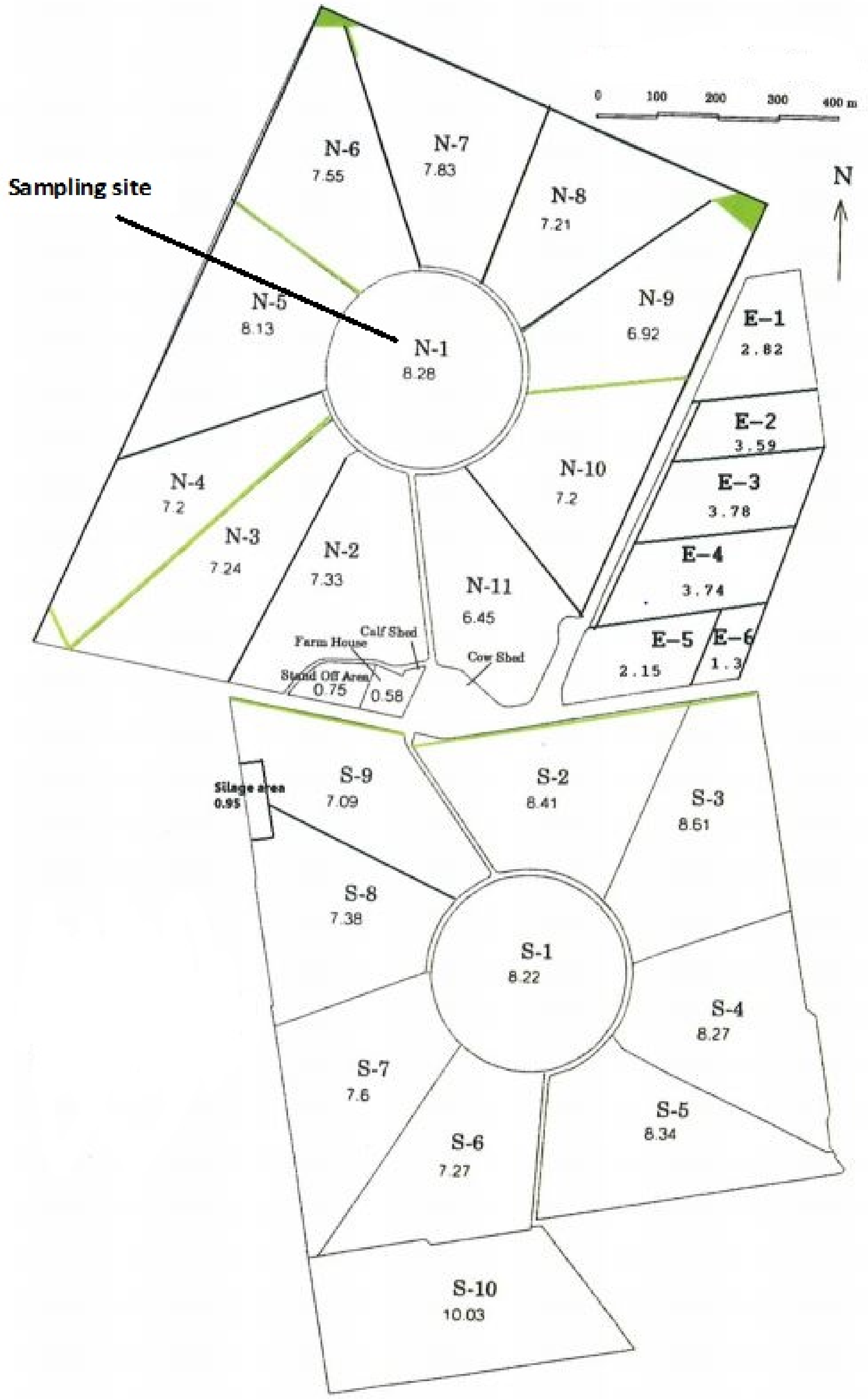
A.1 Soil particle size

Site	Coarse sand 2-0.6 mm Average	Med Sand 0.6-0.2 mm Average	Fine Sand 0.2-0.06 mm Average	Total sand 2-0.06mm Average	Silt 0.06-0.002 mm Average	Clay <0.002 mm Average
DF 0-10 cm	0.0	2.3	15.7	18.0	60.7	21.3
DF 10-20 cm	0.0	1.3	17.0	18.3	60.0	21.7
DF 20-30 cm	0.0	2.0	17.3	19.3	59.7	21.0
SF 0-10 cm	0.0	5.7	27.3	33.0	48.7	18.3
SF 10-20 cm	0.0	5.0	29.0	34.0	48.3	17.7
SF 20-30 cm	0.0	5.7	30.7	36.3	46.0	17.7
CS 0-10 cm	0.0	3.3	24.7	28.0	54.3	17.7
CS 10-20 cm	0.0	3.3	24.7	28.0	53.3	18.7
CS 20-30 cm	0.0	2.9	25.6	28.4	53.2	18.3

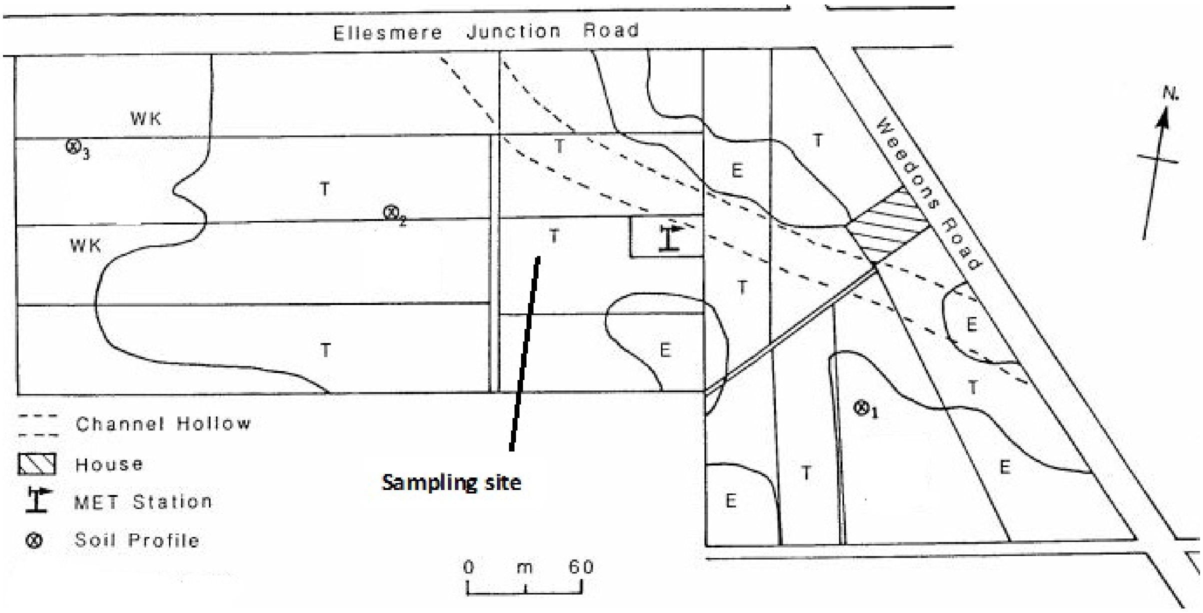
A.2 LUDF fertiliser history

Fertiliser history							
Date	**Dressing**	**N**	**P**	**K**	**S**	**Mg**	**Ca**
Season 2001/02		200	168	-	130	-	94
Season 2002/03		200	45	-	2	-	90
Season 2003/04		200	45	-	64	-	46
Season 2004/05		200	46	-	47	-	57
Season 2005/06	Non-effluent	200	48	-	76	-	107
Season 2005/06	Effluent	0	30	-	53		67
Season 2006/07	Non-effluent	200	49	-	89	-	110
Season 2006/07	Effluent	0	20	-	52	-	45
Season 2007/08	Non-effluent	200	44	-	73	-	96
Season 2007/08	North effluent	12	22	-	37	-	48
Season 2008/09	Non-effluent	245	53	-	88	-	115
Season 2008/09	North effluent	0	22	-	37	-	48
Season 2009/10	Non-effluent	225	45	-	47	-	20
Season 2009/10	Effluent	-	5	-	47	-	20
Season 2010/11	Non-effluent	325	50	-	95	-	111
Season 2010/11	Effluent	-	20	-	57	-	45

A.3 Site maps



Site map 1 LUDF (DF), sample paddock N 1



Site map 2 Sheep grazed, dryland (SF)

Site map 3 Sample sites for sheep grazed, dryland (SF) and control site (CS)

Site map 4 Sample sites for irrigated dairy (DF), dryland sheep grazed (SF) and control site (CS)

A.4 Transect locations, NZTM

	Site		
Pit	DF	SF	CS
1	E1555033 N5167961	E1556087 N5167430	E1556161 N5167305
2	E1555037 N5167961	E1556093 N5167430	E1556161 N5167310
3	E1555042 N5167962	E1556098 N5167431	E1556166 N5167306
4	E1555047 N5167962	E1556103 N5167432	E1556166 N5167311
5	E1555033 N5167956	E1556087 N5167426	E1556170 N5167307
6	E1555037 N5167956	E1556093 N5167426	E1556170 N5167312
7	E1555042 N5167957	E1556098 N5167427	E1556174 N5167308
8	E1555047 N5167957	E1556103 N5167428	E1556174 N5167313
9	E1555033 N5167950	E1556087 N5167421	E1556179 N5167308
10	E1555037 N5167950	E1556093 N5167421	E1556179 N5167314
11	E1555042 N5167951	E1556098 N5167422	E1556183 N5167311
12	E1555047 N5167951	E1556103 N5167423	E1556183 N5167316
13	E1555033 N5167945	E1556087 N5167417	E1556180 N5167307
14	E1555037 N5167945	E1556093 N5167418	E1556183 N5167303
15	E1555042 N5167946	E1556098 N5167418	E1556185 N5167302

A.5 Soil profiles

Soil profile 1 Irrigated dairy (DF)

Soil profile 2 Dryland sheep grazed (SF)

Soil profile 3 Control site (CS)

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